New Constraints on Sterile Neutrino Oscillations from MINOS, Daya Bay, and Bugey-3

Adam Aurisano
University of Cincinnati

On behalf of the MINOS collaboration

En-Chuan Huang
Los Alamos National Laboratory
University of Illinois at Urbana-Champaign

On behalf of the Daya Bay collaboration

Fermilab Wine-and-Cheese Seminar
September 2nd, 2016

Outline

- Introduction to sterile neutrino
- Daya Bay
- Daya Bay + Bugey-3
- MINOS
- Daya Bay + Bugey-3 + MINOS

This talk contains results reported in three papers:
Daya Bay : arXiv:1607.01174
MINOS : arXiv:1607.01176
Combined : arXiv:1607.01177
Accepted for publication by PRL

3-flavor Neutrino Oscillation

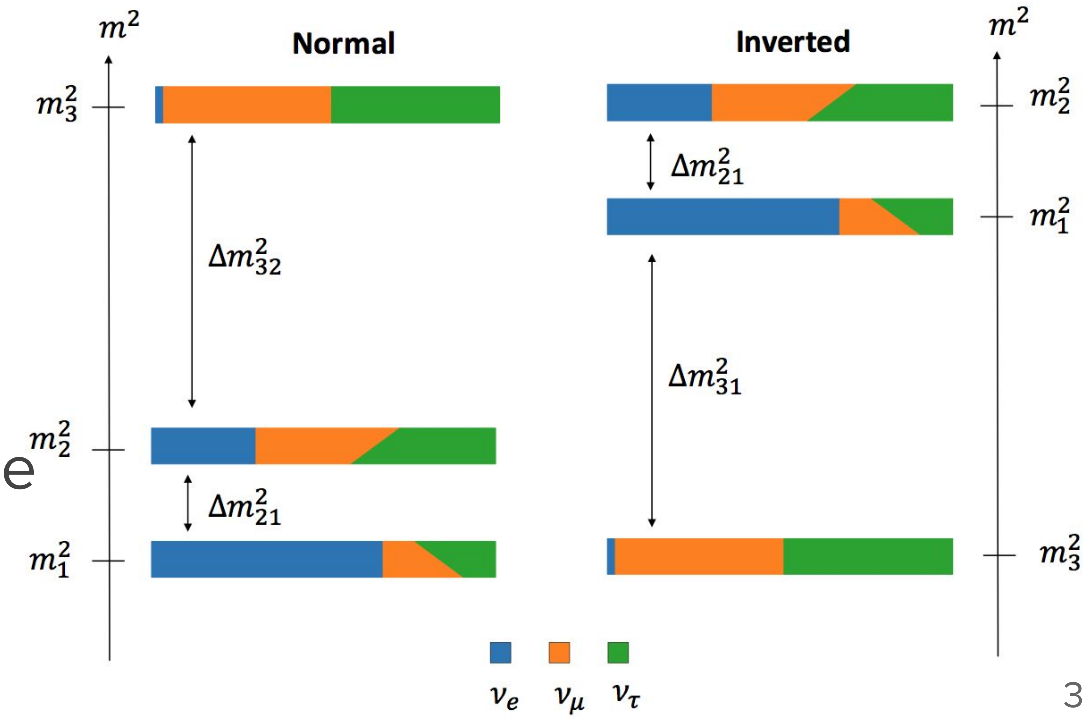
$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij} \qquad c_{ij} = \cos\theta_{ij}$$

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

- 3-flavor picture is well established by solar, atmospheric, reactor, and accelerator experiments
- Daya Bay and MINOS were both designed to study neutrino oscillation

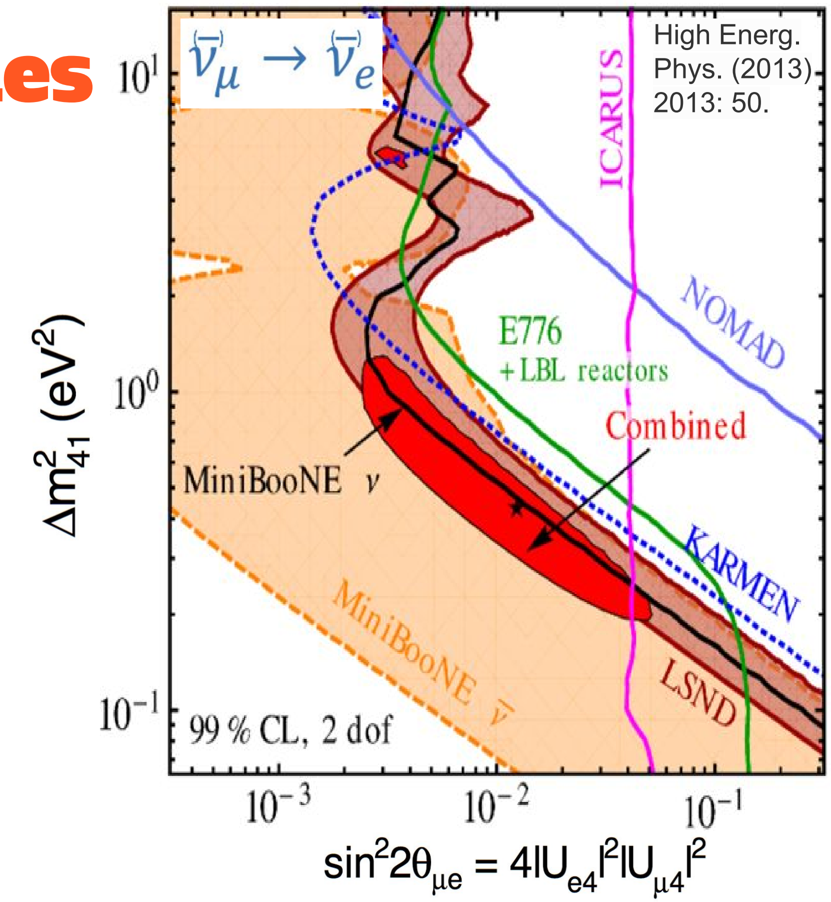


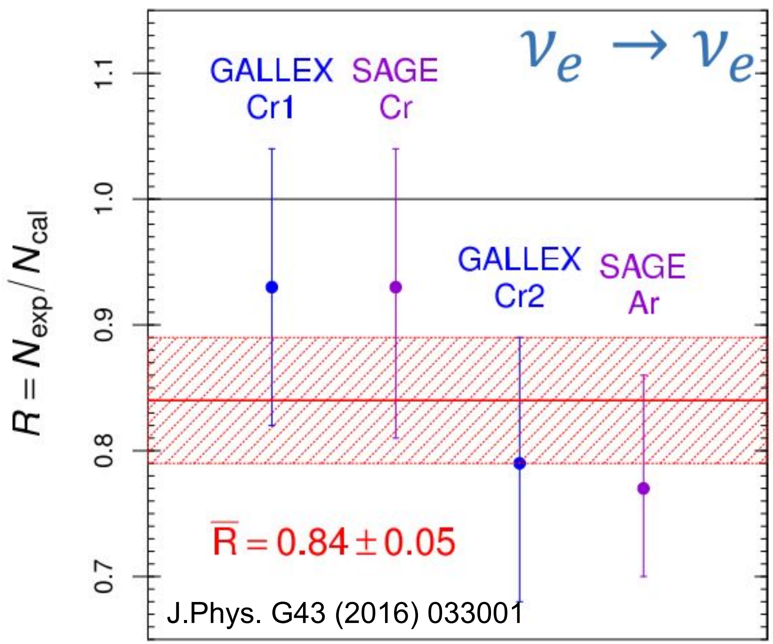
Experimental Anomalies

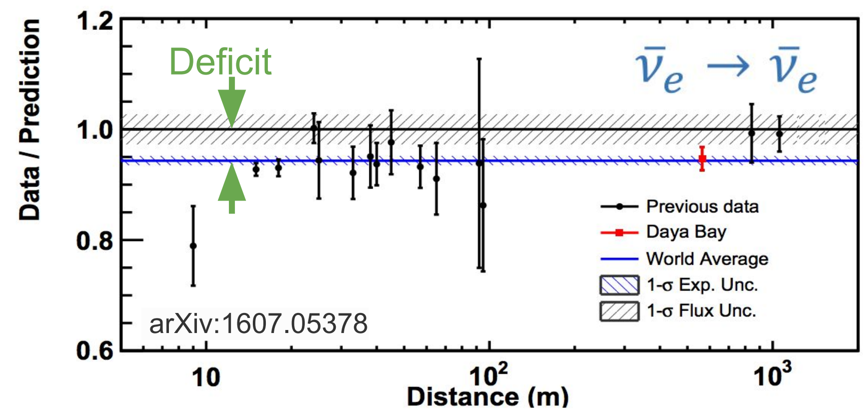
$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$: LSND & MiniBooNE

$\bar{\nu}_e \rightarrow \bar{\nu}_e$: Reactor $\bar{\nu}_e$ anomaly

$\nu_e \rightarrow \nu_e$: Gallium anomaly

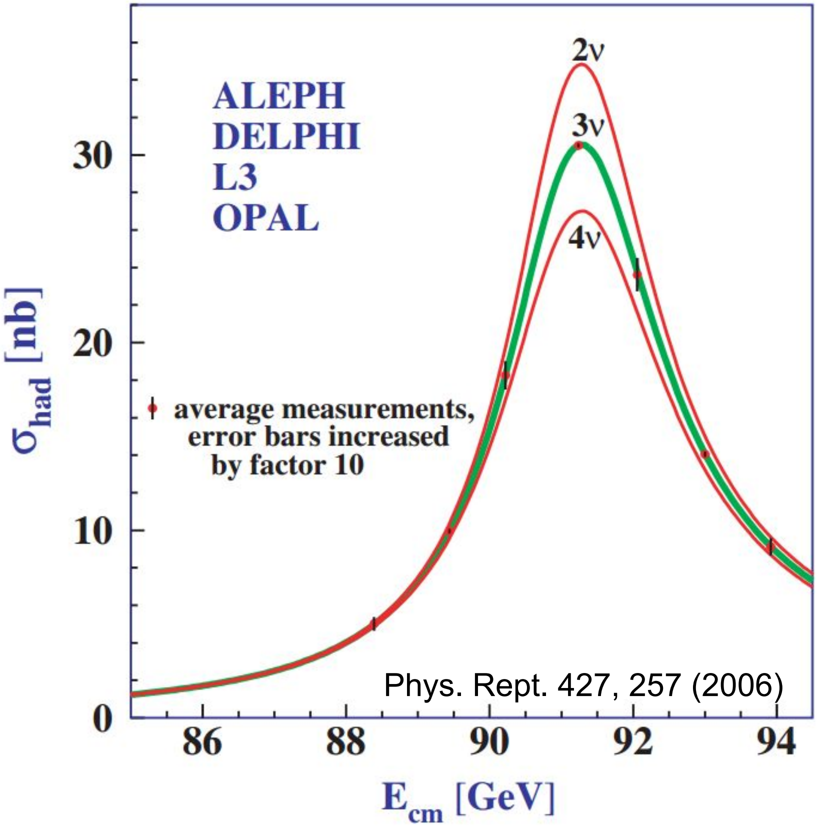






Three Active Neutrinos

- Only three light active neutrino flavors
- Any other neutrino species would be sterile -- not interacting via weak interaction
- Still observable via neutrinc oscillation



3+1 Formalism

$$U = \begin{pmatrix} \boxed{U_{e1} \quad U_{e2} \quad U_{e3} \quad U_{e4}} \\ \boxed{U_{\mu 1} \quad U_{\mu 2} \quad U_{\mu 3} \quad U_{\mu 4}} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

For Daya Bay $\bar{\nu}_e \rightarrow \bar{\nu}_e$

For MINOS $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu$

For LSND & MiniBooNE $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$

$$P_{\nu_\mu \rightarrow \nu_e}(L/E) \approx 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \approx P_{\overline{\nu}_\mu \rightarrow \overline{\nu}_e} \quad , \Delta m^2_{41} \gg |\Delta m^2_{32}|$$

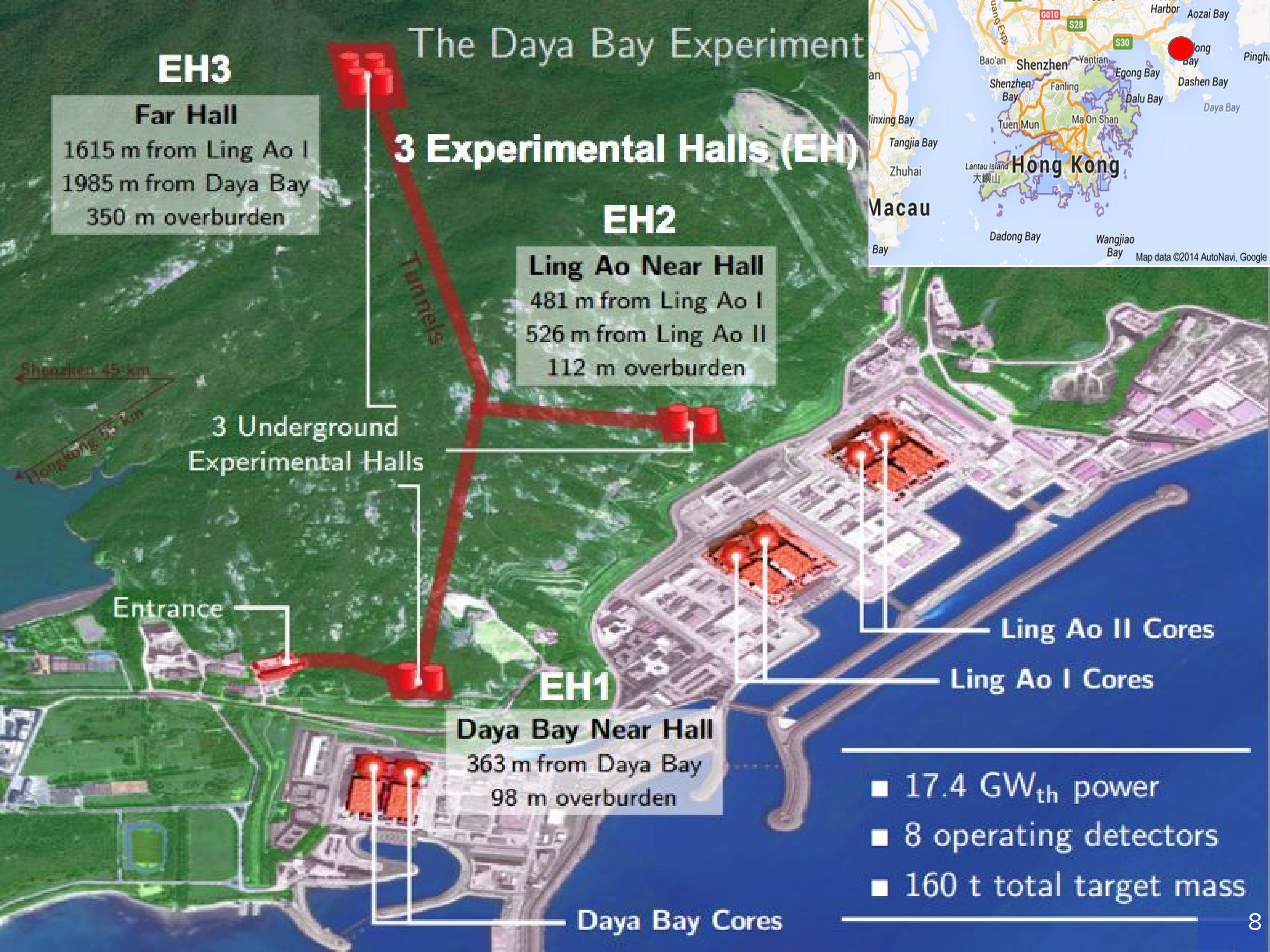
Define $U = R_{34}R_{24}R_{14}R_{23}R_{13}R_{12}$

$$|U_{e4}|^2 = \sin^2\theta_{14}\,, \qquad \text{Daya Bay}$$

$$|U_{\mu 4}|^2 = \sin^2\theta_{24}\cos^2\theta_{14}\,, \qquad \text{MINOS}$$

$$4|U_{e4}|^2|U_{\mu 4}|^2 = \sin^2 2\theta_{14}\sin^2\theta_{24} \equiv \sin^2 2\theta_{\mu e} \qquad \text{LSND\& MiniBooNE}$$

Daya Bay

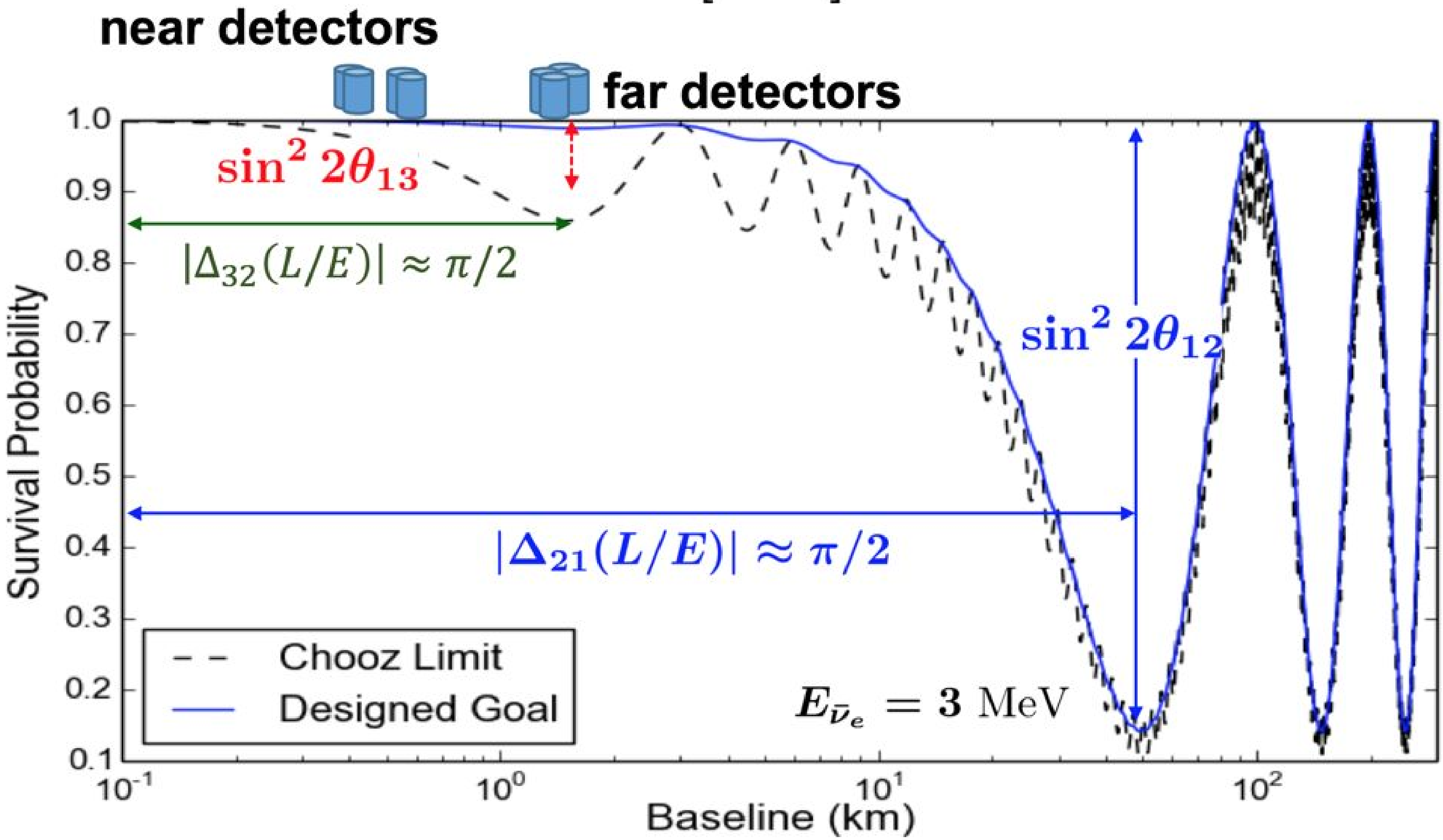


- $17.4\ GW_{th}$ power
- 8 operating detectors
- 160 t total target mass

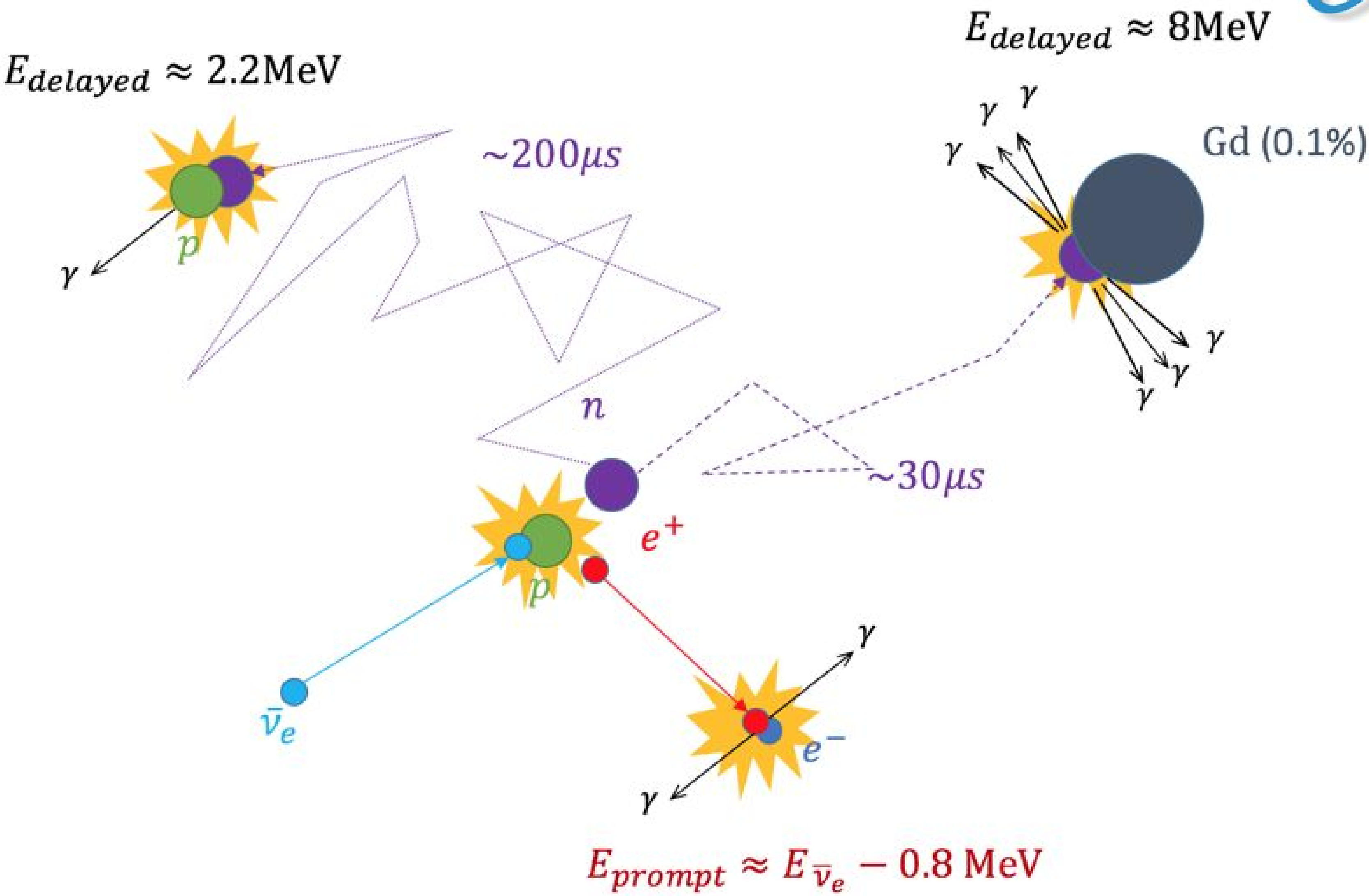
Design of Daya Bay   Find → θ_{13}

$$P_{\bar{\nu}_e\to\bar{\nu}_e}(L) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right)$$

$$\Delta_{ij}(L/E) \equiv 1.267\Delta m^2_{ij}\,[\mathrm{eV}^2]\frac{L[\mathrm{m}]}{E[\mathrm{MeV}]}$$



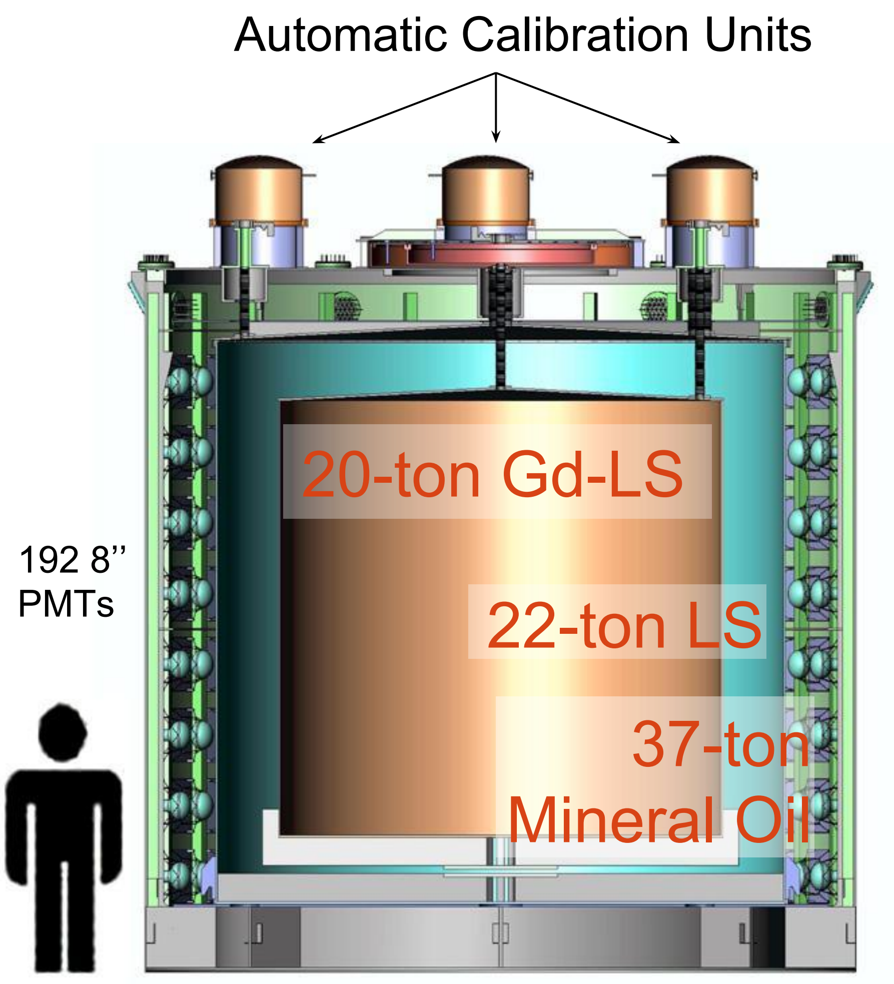
Detection Method



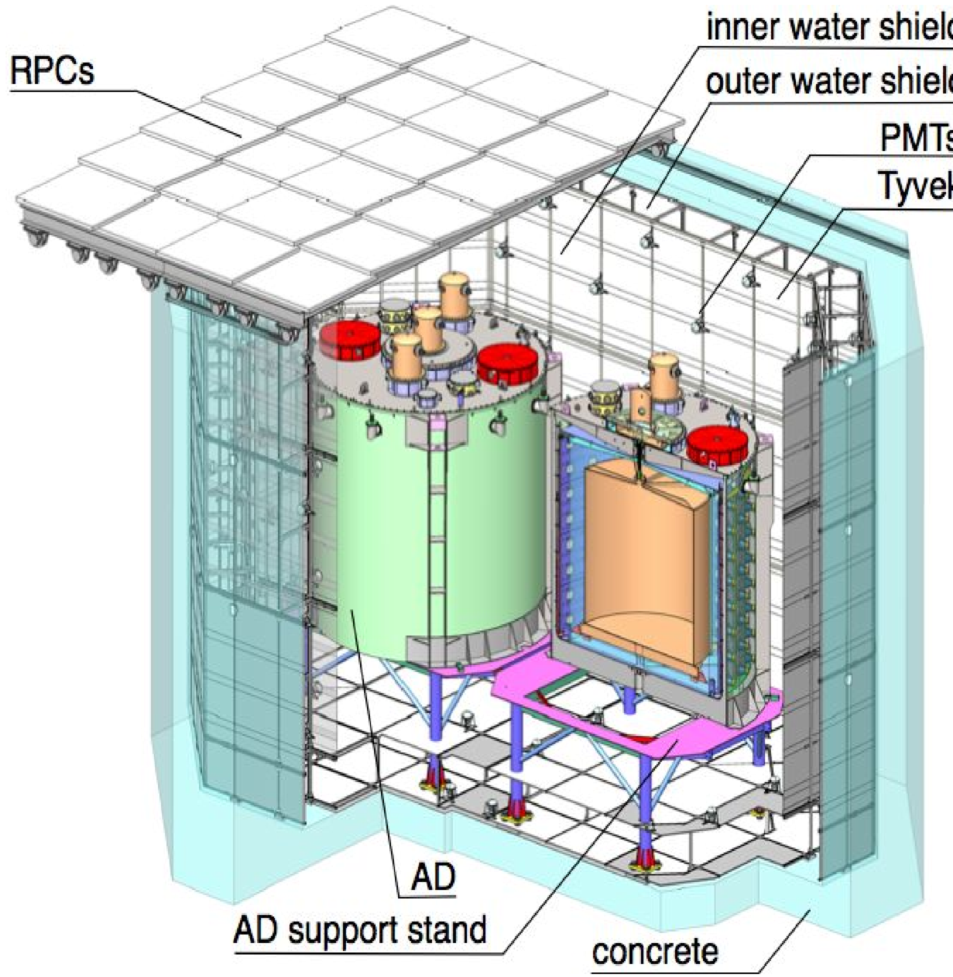
The coincidence between prompt and delayed signal provides powerful background rejection

Antineutrino Detector (AD)

- Three-zoned Antineutrino Detectors (ADs) are immersed in water pools, served as muon taggers and radiation shield



NIM. A 811(2016) 133-161



Nucl. Instrum. Meth. A 773, 8 (2015)

Installation of ADs

217 days

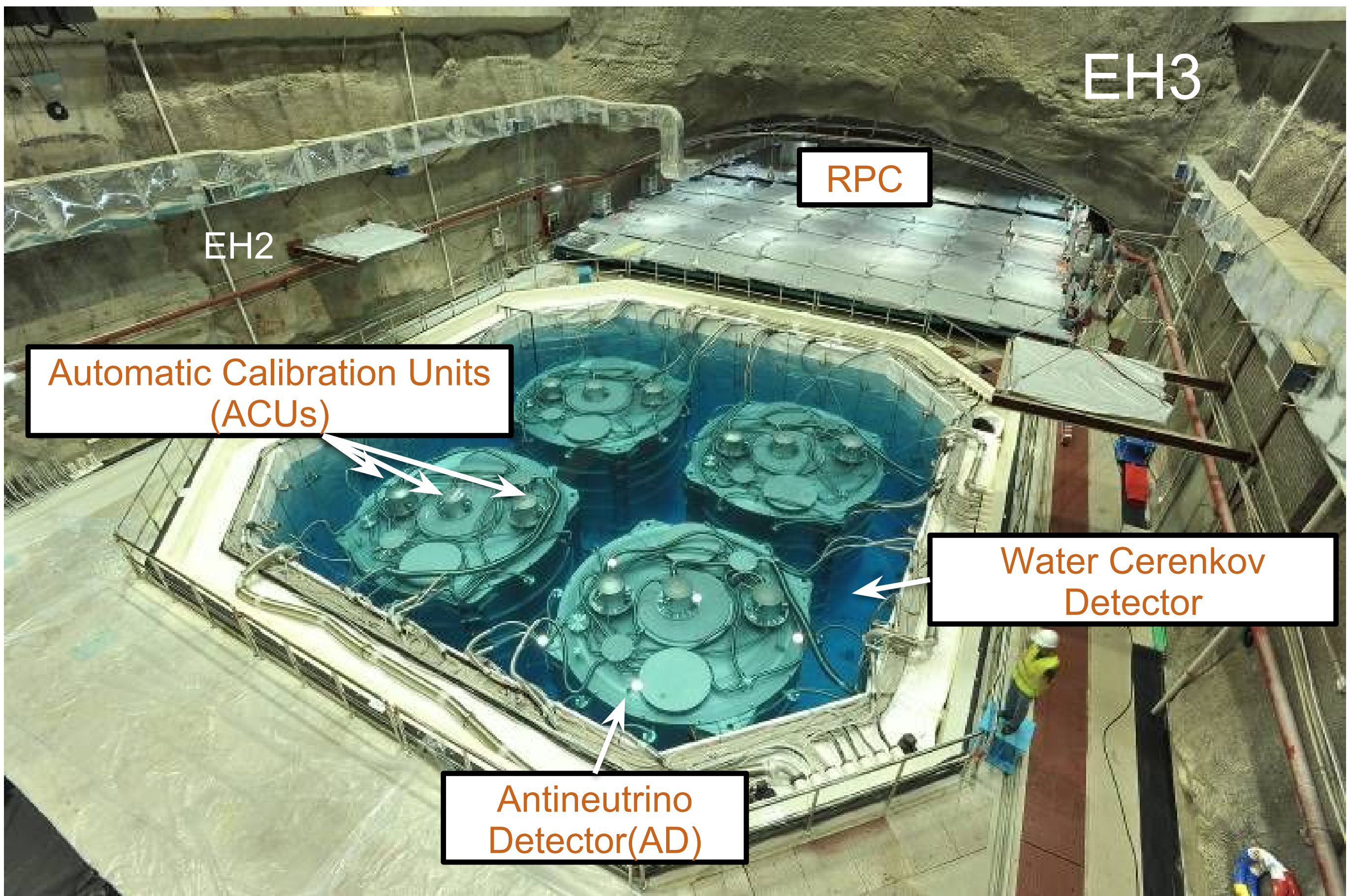
6-AD

8-AD Data Taking

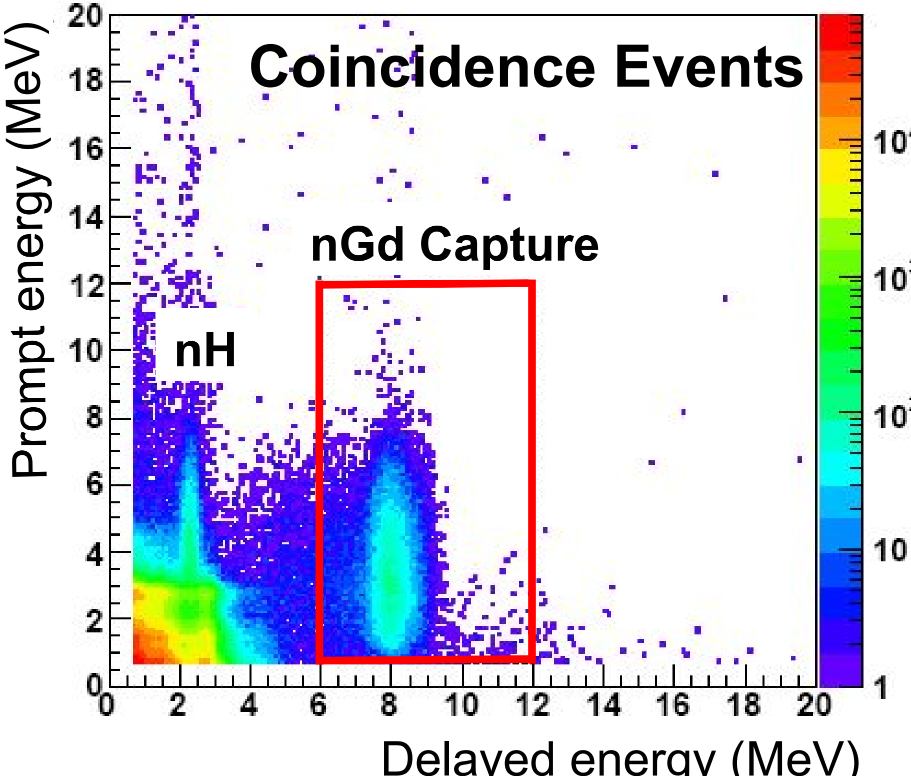
2012 2013 2014 2015 2016

621-day data
Sterile results

1230-day data
3ν results



Antineutrino Selection



Select IBD Events if

$0.7\ \mathrm{MeV} < E_{prompt} < 12.0\ \mathrm{MeV}$

$6.0\ \mathrm{MeV} < E_{delayed} < 12.0\ \mathrm{MeV}$

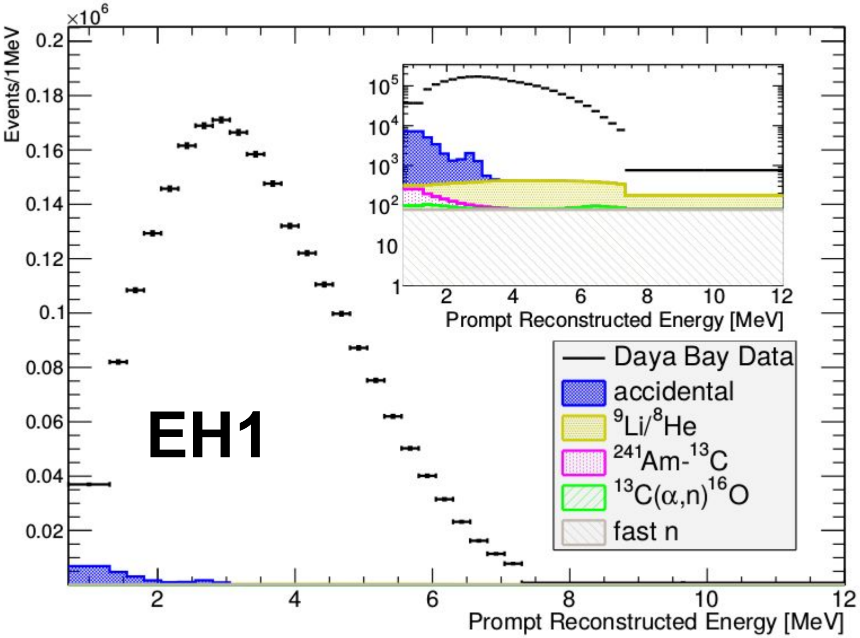
$1\ \mu s < t_{prompt-delayed} < 200\ \mu s$

Reject

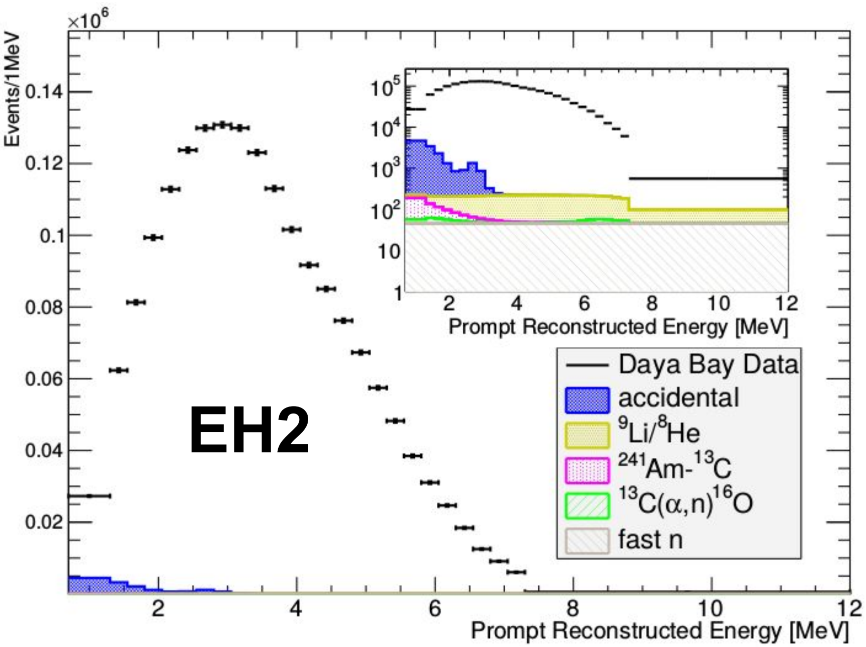
- **Muons tagged by either water Cerenkov detectors or AD (ε_{μ}=0.82, 0.86, and 0.98 for EH1, EH2, and EH3)**
- **Flashers: spontaneous PMT light emission**
- **Events with more than one coincidence (multiplicity cut) (ε_{m}=0.97, 0.98, and 0.98 for EH1, EH2, and EH3)**

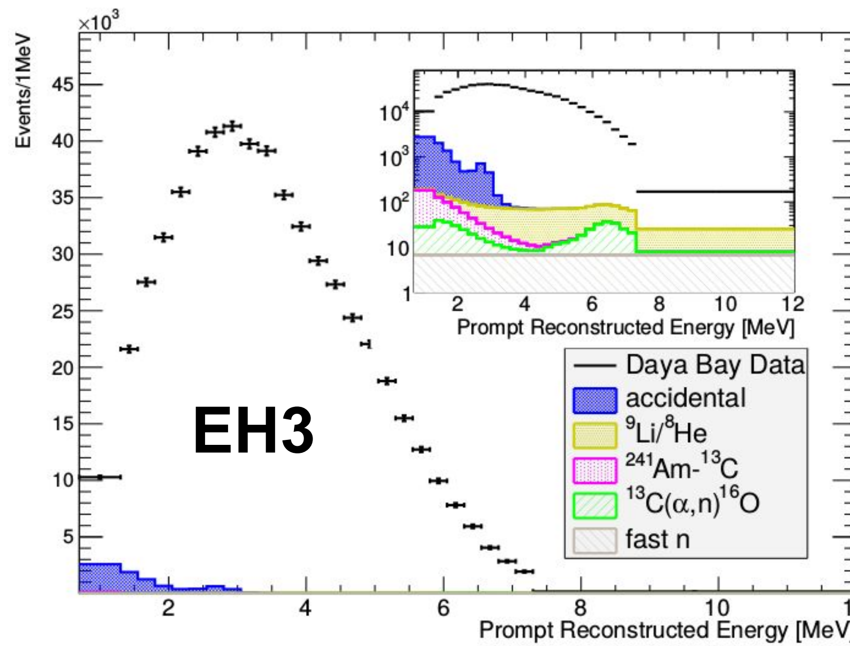
Energy Spectra

621 days



Site	IBD candidates	
	(6-AD)	(8-AD)
EH1	205135	408678
EH2	93742	383402
EH3	41348	108907

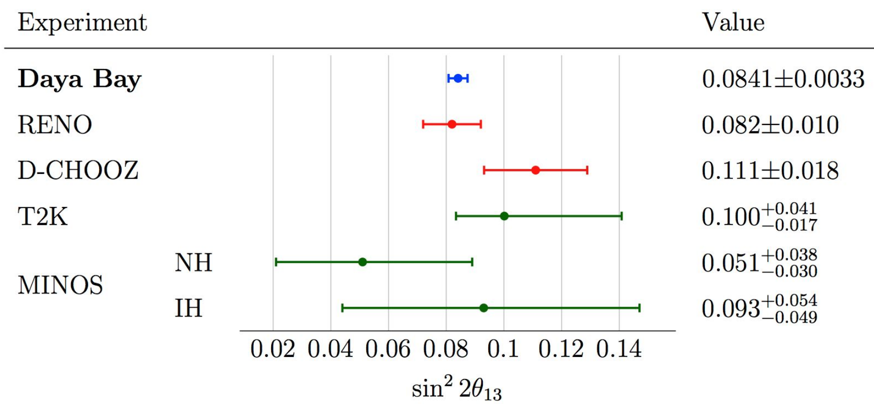


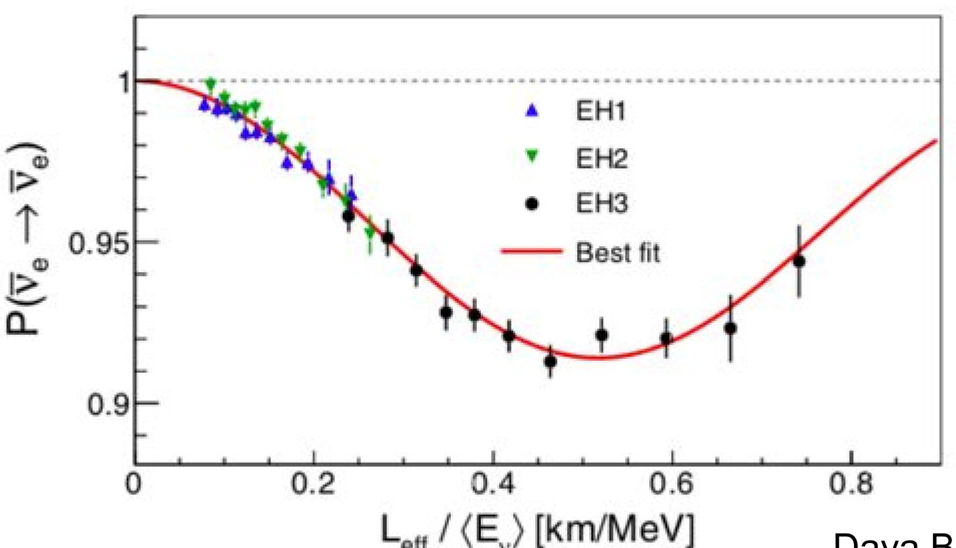


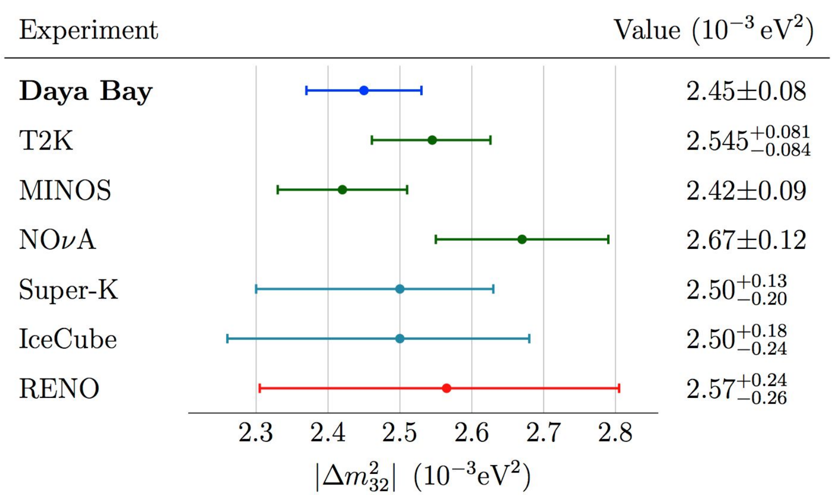
3-flavor Oscillation Results

1230 days

$$\sin^2 2\theta_{13} = 0.0841 \pm 0.0033$$
$$\Delta m^2_{32}(\mathrm{NH}) = [2.45 \pm 0.08]\times 10^{-3}\ \mathrm{eV}^2$$
$$\Delta m^2_{32}(\mathrm{IH}) = [-2.55 \pm 0.08]\times 10^{-3}\ \mathrm{eV}^2$$

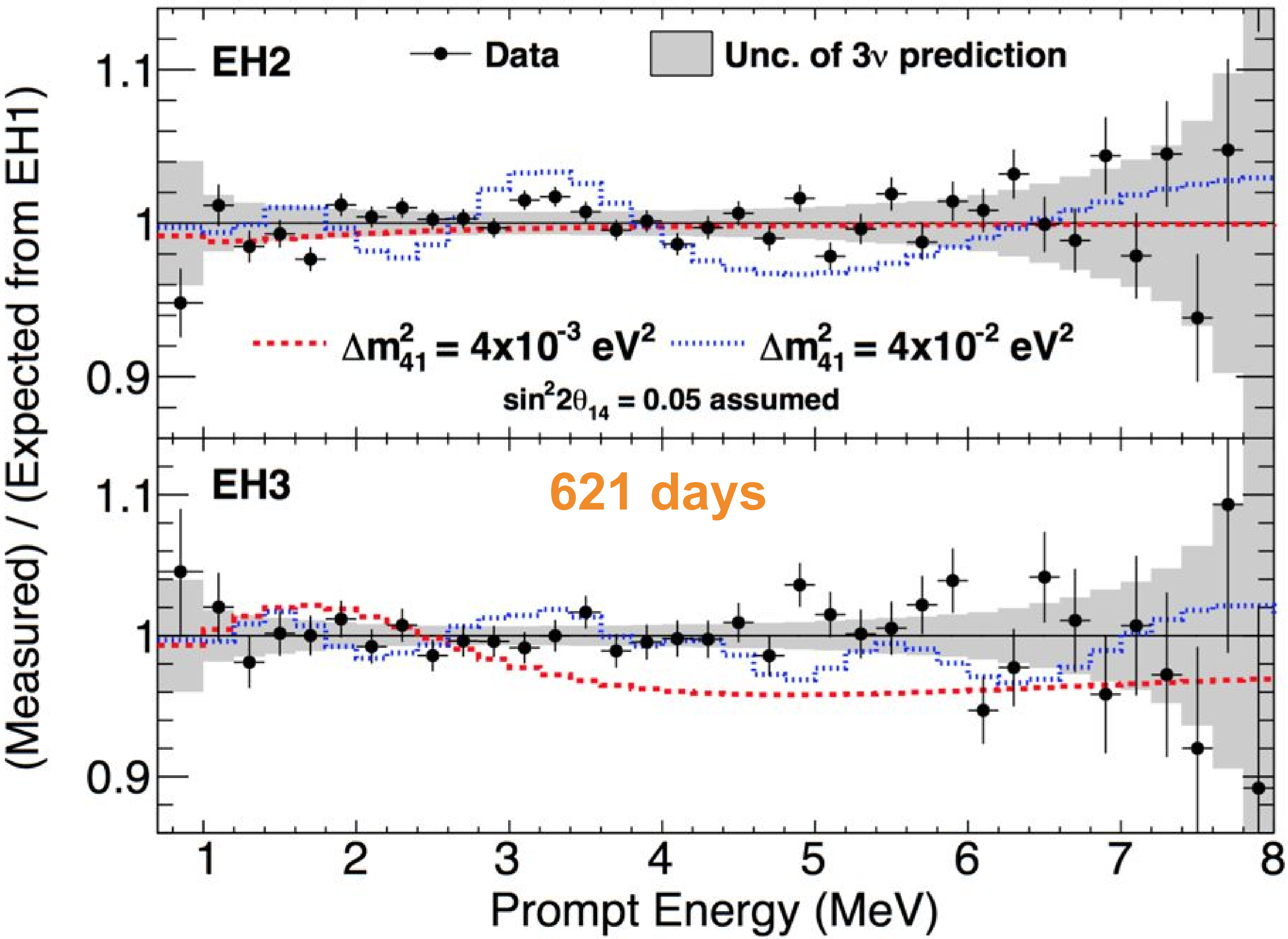






Daya Bay@Neutrino16

If a Light Sterile Neutrino Exists...



Analyses

- Two independent analyses

	Event Prediction	χ^2
Analysis A	Near → Far	Full covariance matrix
Analysis B	Huber + Mueller model Enlarged error	Pull terms + covariance matrix

- Problem: Degree of freedom (DOF) drops when $\sin^2 2\theta_{14} \rightarrow 0$
  - Cannot set confidence level (CL) by $\Delta\chi^2$ based on DOF
- Solution 1: Feldman-Cousin method (Analysis A)
  - C.L. determined by MC simulation of pseudo-experiments
- Solution 2: CL_s method (Analysis B)

CL_s Method

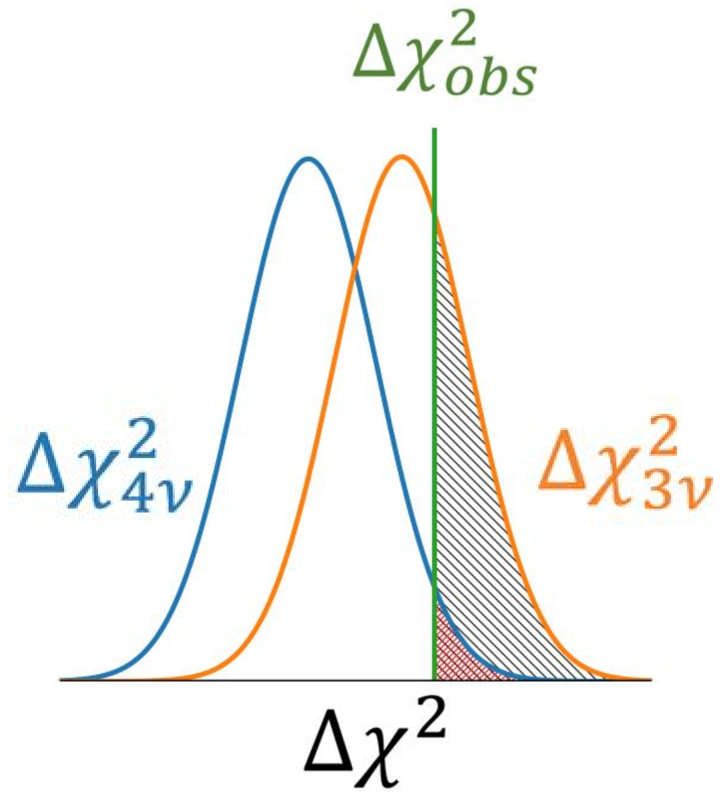
- For each pair of ($\sin^2 2\theta_{14}$, Δm^2_{41}), is the 4ν model much worse than the 3ν model?

$$\Delta\chi^2 = \chi^2_{4\nu} - \chi^2_{3\nu}$$

$$\mathrm{CL_b} = P\left(\Delta\chi^2 \geq \Delta\chi^2_{obs} \middle| 3\nu\right) =$$

$$\mathrm{CL_{s+b}} = P\left(\Delta\chi^2 \geq \Delta\chi^2_{obs} \middle| 4\nu\right) =$$

$$\mathrm{CL_s} = \frac{\mathrm{CL_{s+b}}}{\mathrm{CL_b}} = \quad / $$

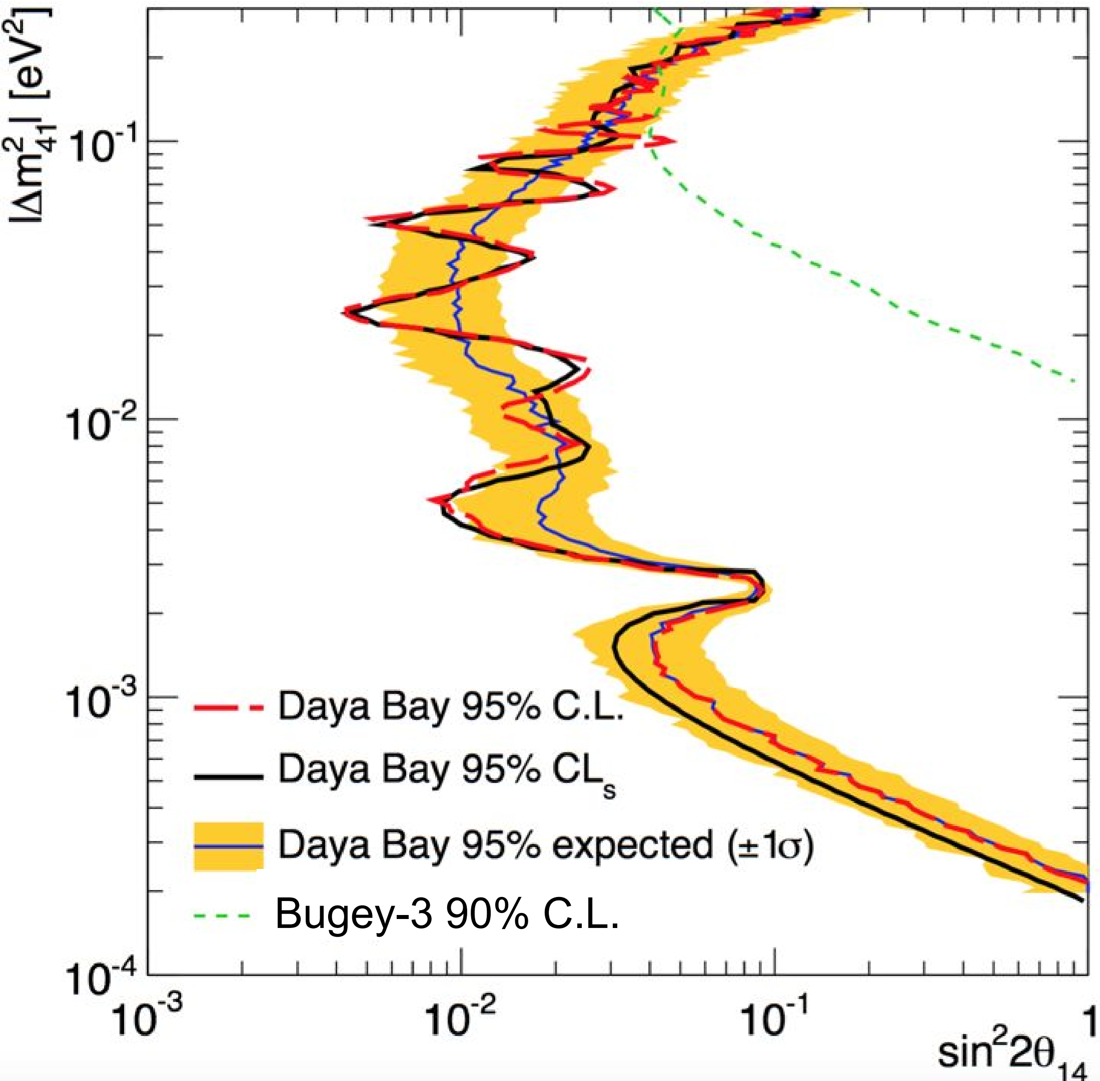


Point is excluded at ≥ (1-α) CL_s, if CL_s < α

CL_s Method

- $\Delta\chi^2$ distribution can be obtained by :
  - MC simulation with pseudo-experiments
  - Use Asimov data set (prediction without fluctuation) for Gaussian approximation (PRD 86 113011 (2012))
- Why CL_s?
  - Solid even when we don't know the DOF
  - Faster if we use Gaussian approximation
  - Great tool for combination (introduced later)

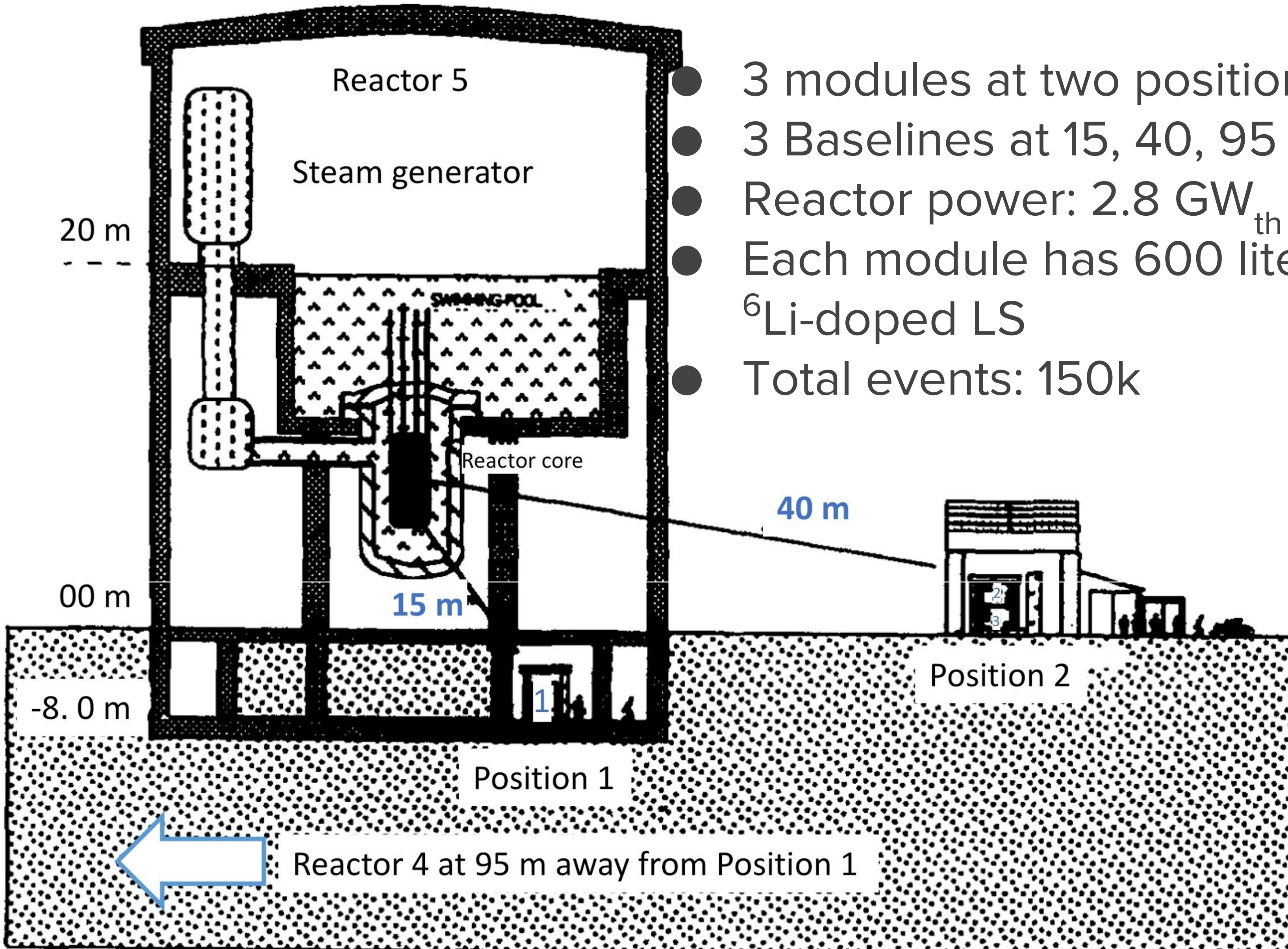
Sterile Neutrino Search



- Consistent results between Analysis A (C.L.) and Analysis B (CL$_s$)
- Constraints on $\sin^2 2\theta_{14}$ improves by a factor of 2 from 6-AD to 621-day data
- Bugey-3 experiment is sensitive to higher Δm^2_{41}

arXiv:1607.01174, accepted by PRL

Bugey-3 Experiment



- 3 modules at two positions
- 3 Baselines at 15, 40, 95 m
- Reactor power: 2.8 GW_{th}
- Each module has 600 liters of ^{6}Li-doped LS
- Total events: 150k

Nucl.Phys. B434 (1995) 503-534, Nucl. Instrum. Meth. A374 (1996) 164-187

Bugey-3's Data

- Input : Observed / MC with two major modifications
- Modifications in ratios

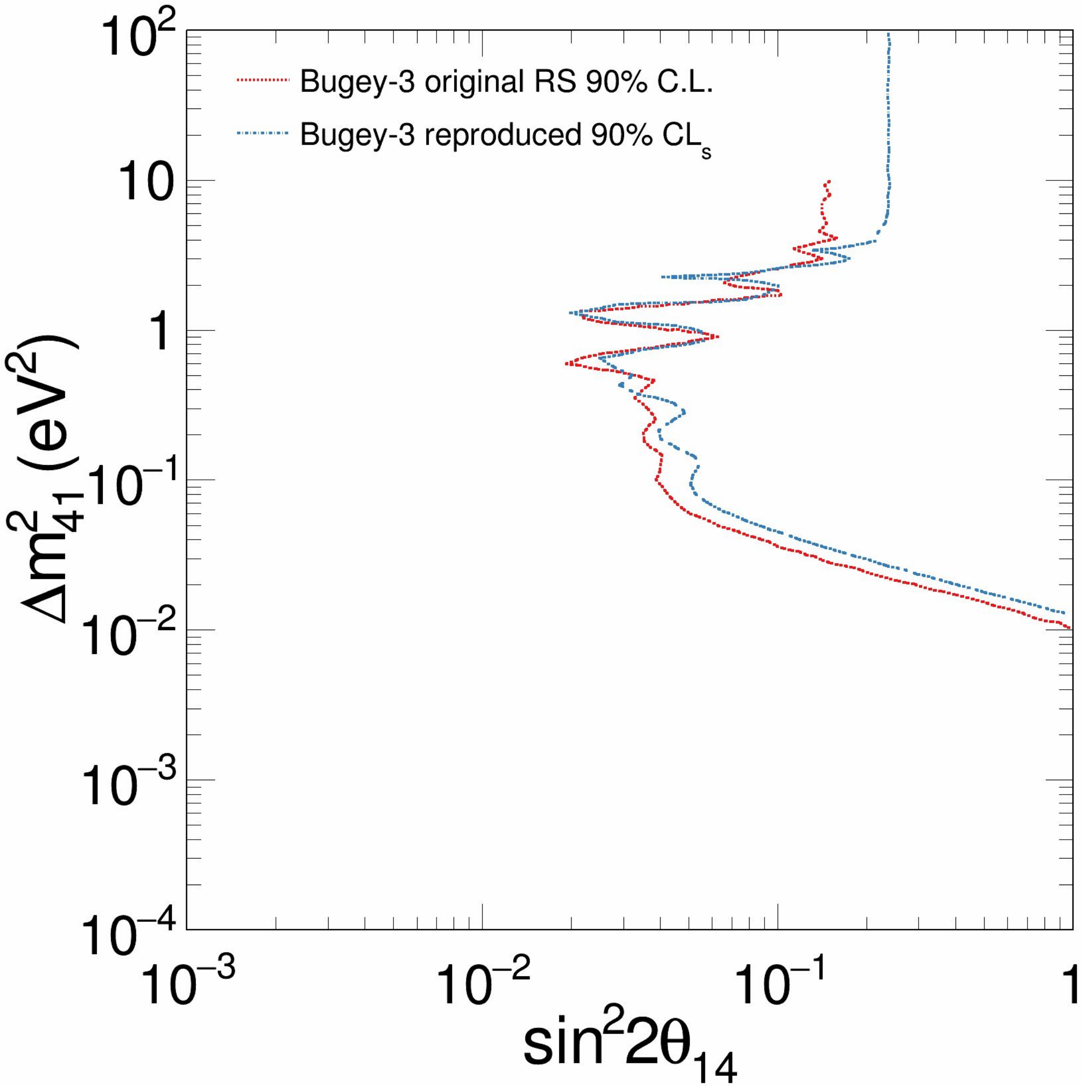
$$R^{obs} = \frac{data}{MC(ILL + Vogel)} \longrightarrow MC(Huber + Mueller)$$

Reactor flux Daya Bay is using

$$R'^{obs} = \frac{data}{MC(ILL + Vogel)} \frac{MC(ILL + Vogel)}{MC(Huber + Mueller)}$$

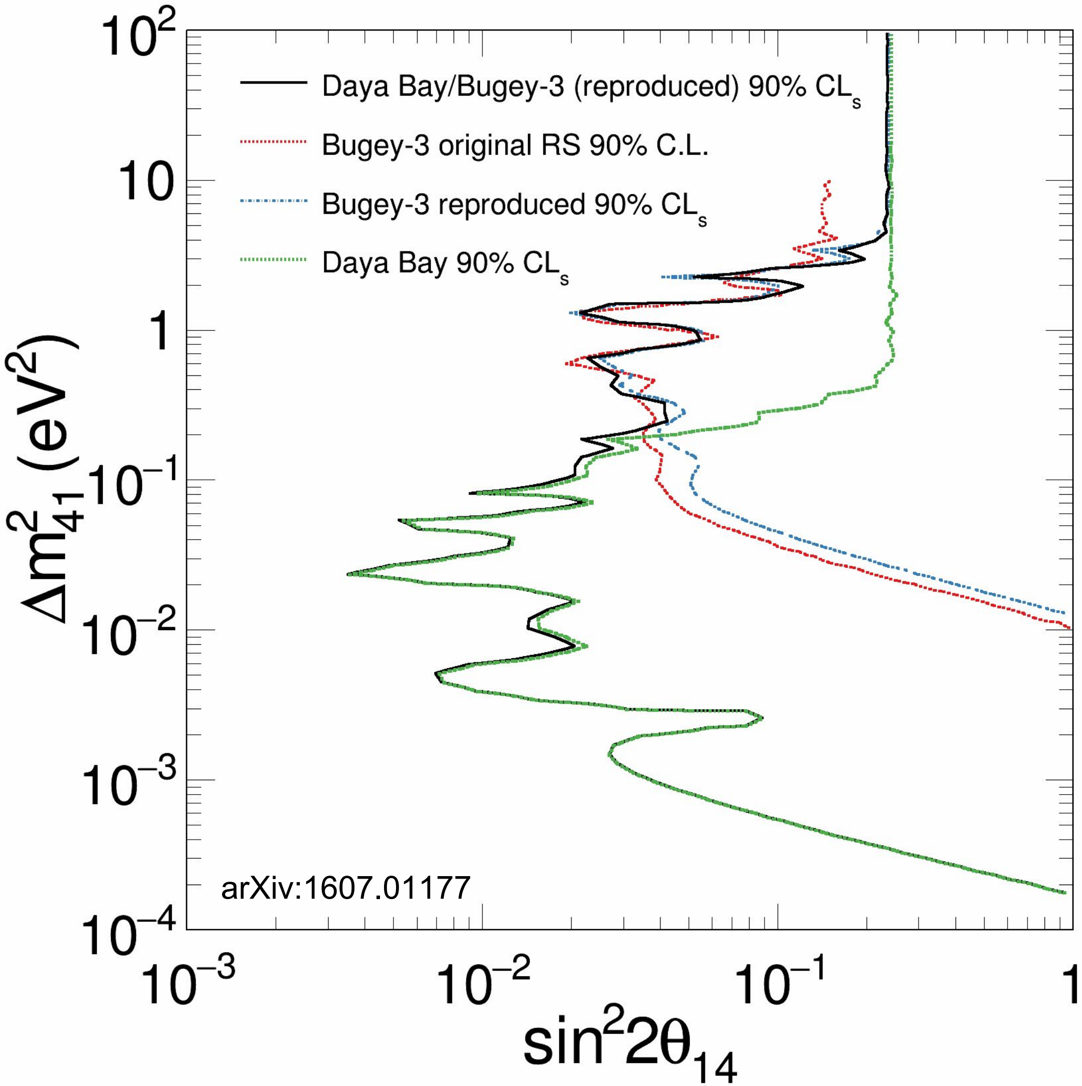
- Modifications in cross sections:
  - Cross section is inversely proportional to neutron lifetime

Bugey-3 Contour (Reproduced)



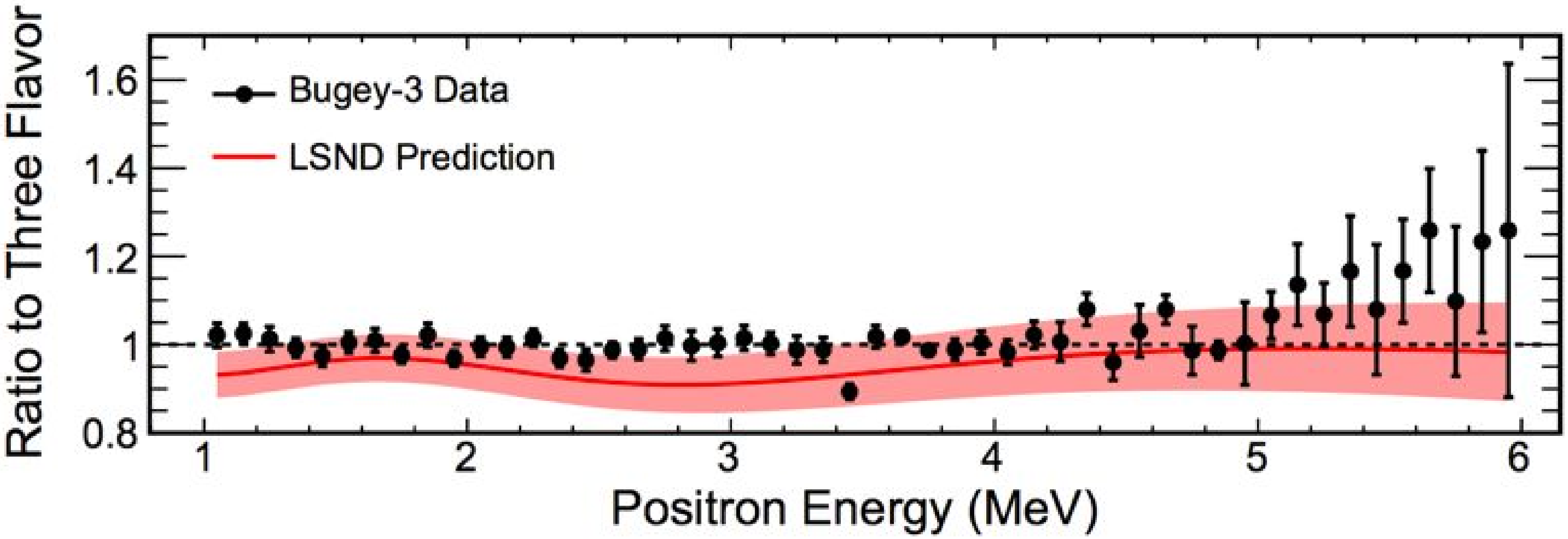
- Consistent results between our reproduced contour and the original Bugey's flux in raster scan (RS)
- Similar exclusion region for the reproduced one with updated flux

Daya Bay + Bugey-3



- Fitted with common normalization and oscillation parameters
- CL_s method is used for further combination with MINOS
- The combined analysis extends the exclusion region to larger Δm^2_{41} region

If a Light Sterile Neutrino Exists...



At LSND best fit point $\Delta m^2_{41} = 1.2\ \mathrm{eV}^2$, $\sin^2 2\theta_{\mu e} = 0.003$
$\sin^2\theta_{24} = 0.027$ (MINOS 90% C.L. at $\Delta m^2_{41}=1.2\ \mathrm{eV}^2$)
$\sin^2 2\theta_{14} = 0.11$

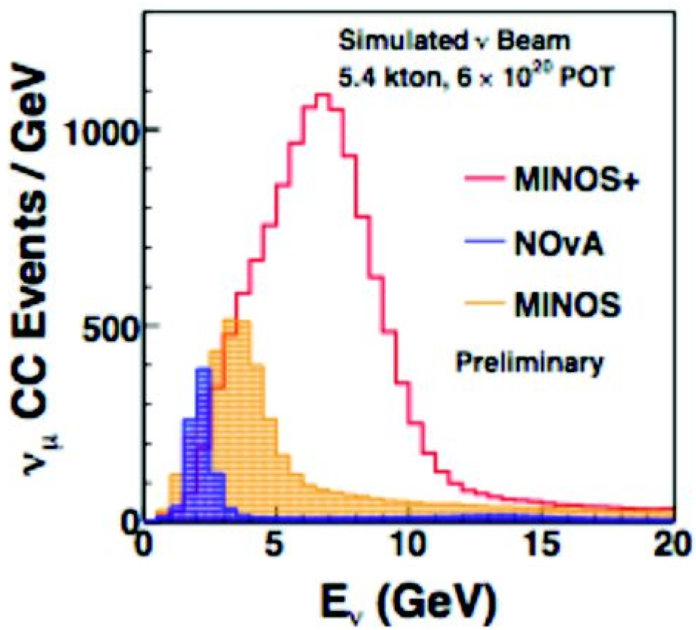
MINOS

MINOS Overview

- NuMI neutrino beam from 120 GeV Main Injector-accelerator protons
- Measure neutrinos energy with two functionally identical iron-scintillator tracking calorimeters.
    - Near Detector at Fermilab
        - 1 km from target
        - 1 kton mass
    - Far Detector, deep underground in the Soudan mine
        - 735 km from target
        - 5.4 kton mass

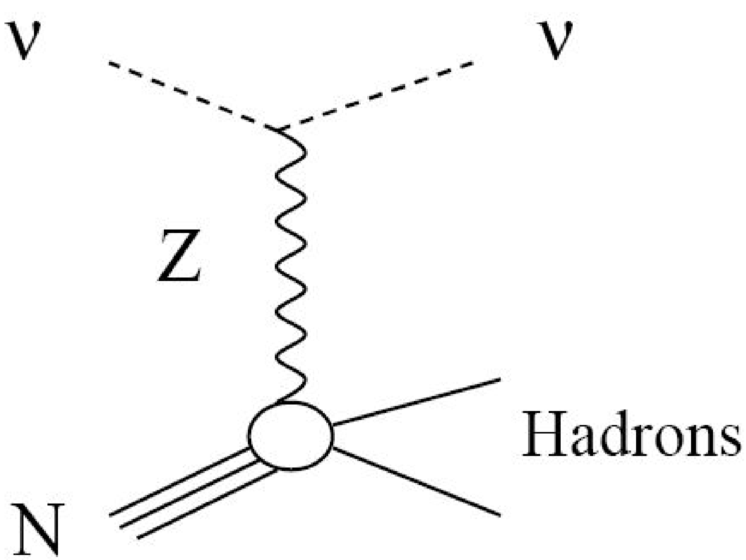
MINOS Overview

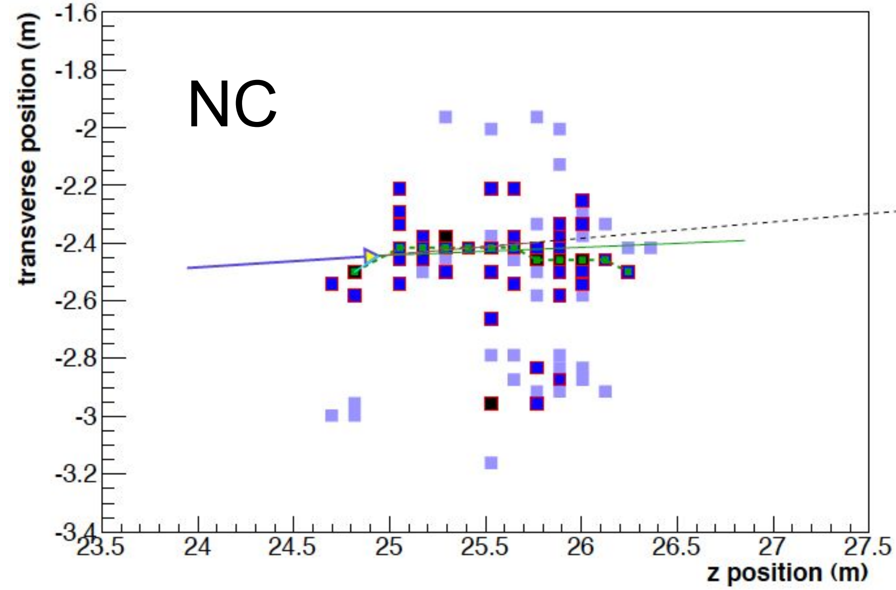
- From 2005-2012, the NuMI beam operated in low-energy mode
  - MINOS era
  - This analysis
- From 2013-2016, the NuMI beam operated in the medium energy mode
  - MINOS+ era



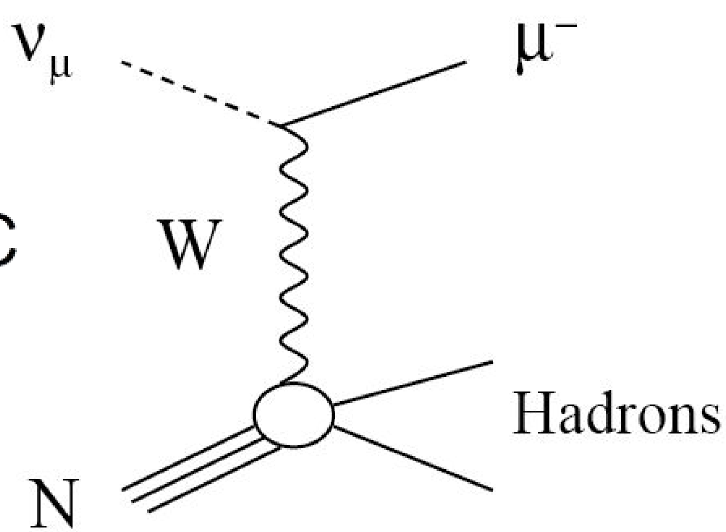
Event Topologies

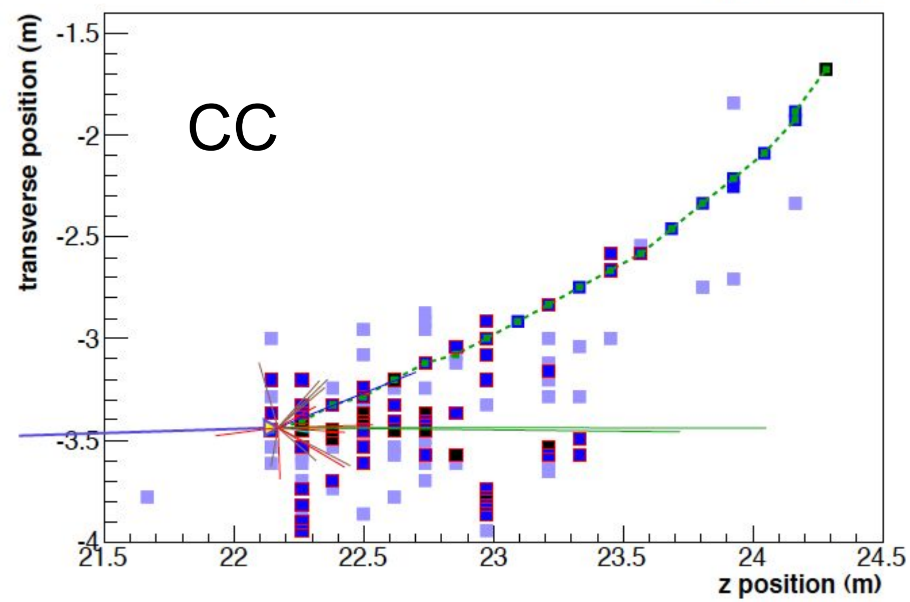
NC





ν_μ CC





Long-Baseline Sterile Searches

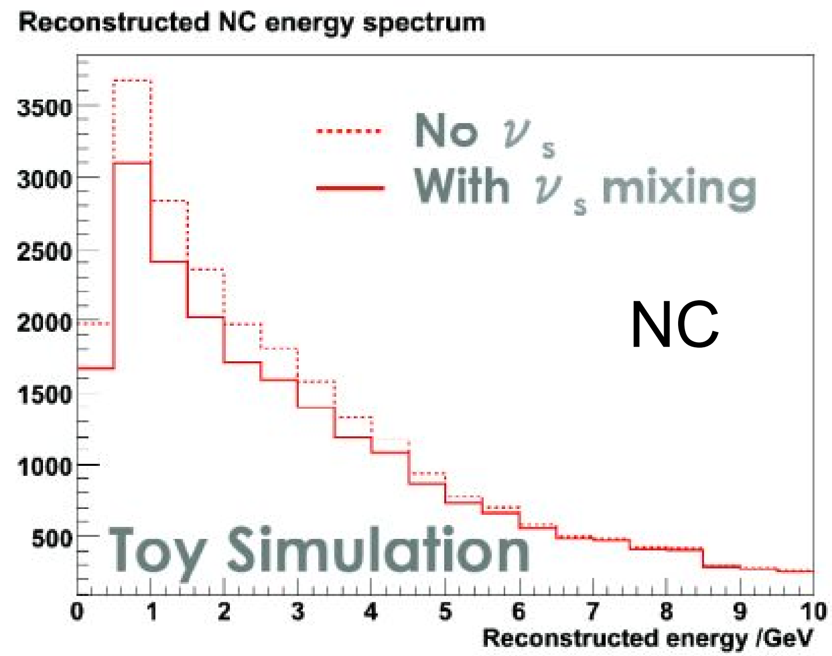
Neutral Current

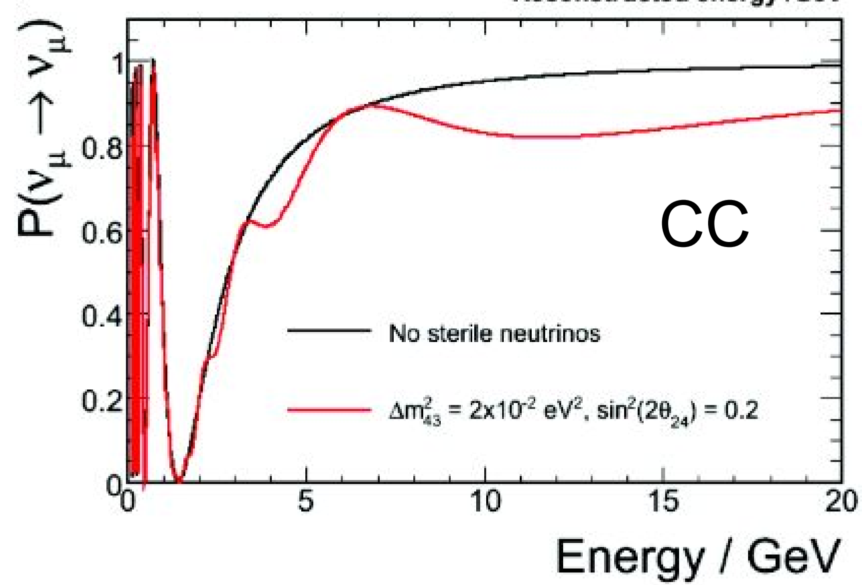
- NC interaction rate is independent of oscillations of the three active flavors.
- $\nu_\mu \rightarrow \nu_s$ oscillations reduce the NC rate as ν_s do not interact in the detector.
- Previously investigated at MINOS
  - Phys.Rev.D81 (2010) 052004
  - Phys.Rev.Lett 107 (2011) 011802

ν_μ Charged Current

- Sterile oscillations add modulations to standard 3-flavor picture.

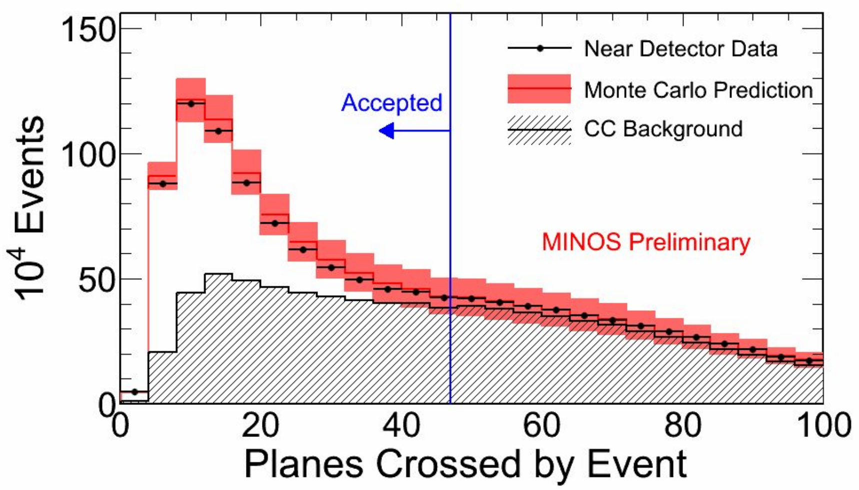
Fit both NC and CC spectra to the 4-flavor model to constrain sterile mixing parameters.

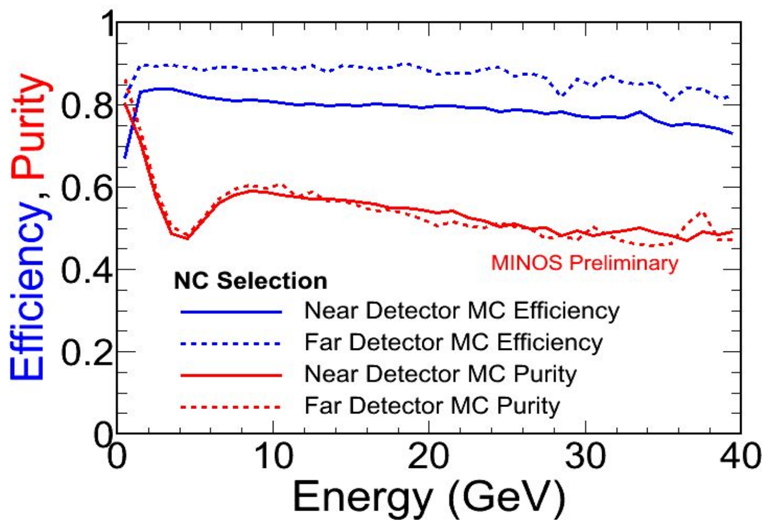


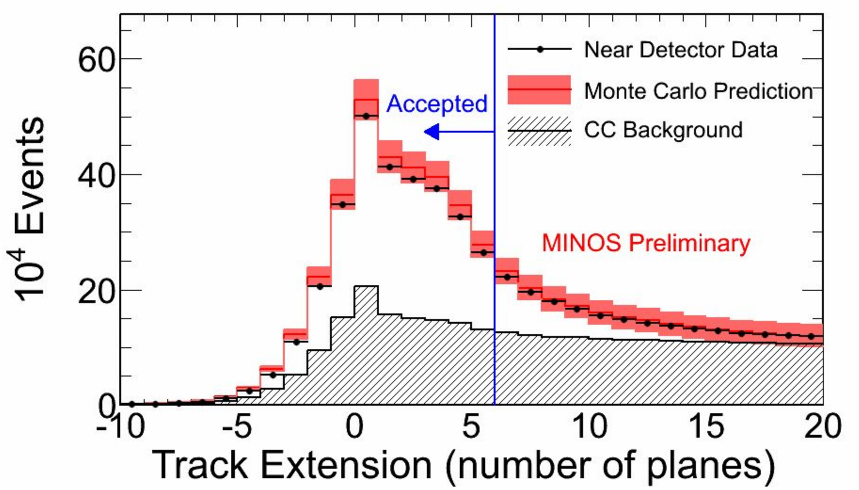


NC Event Selection

NC/CC event separation achieved via cuts on topological quantities.







- 89% efficiency and 61% purity at the FD
- Main background is inelastic ν_μ CC events.
- 97% of ν_e CC events are selected as NC.

NC Event Selection

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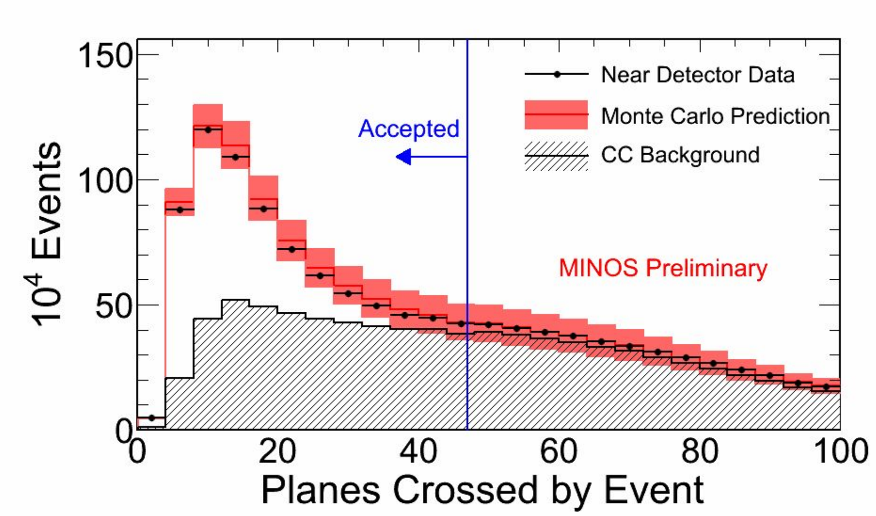

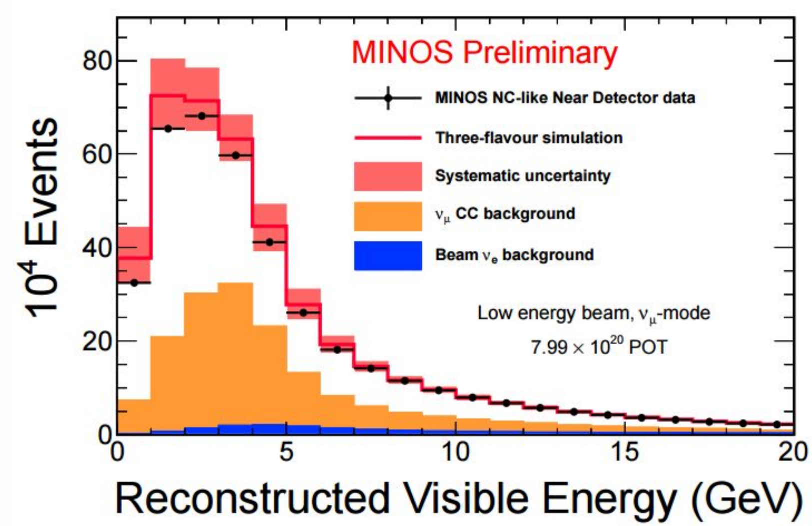

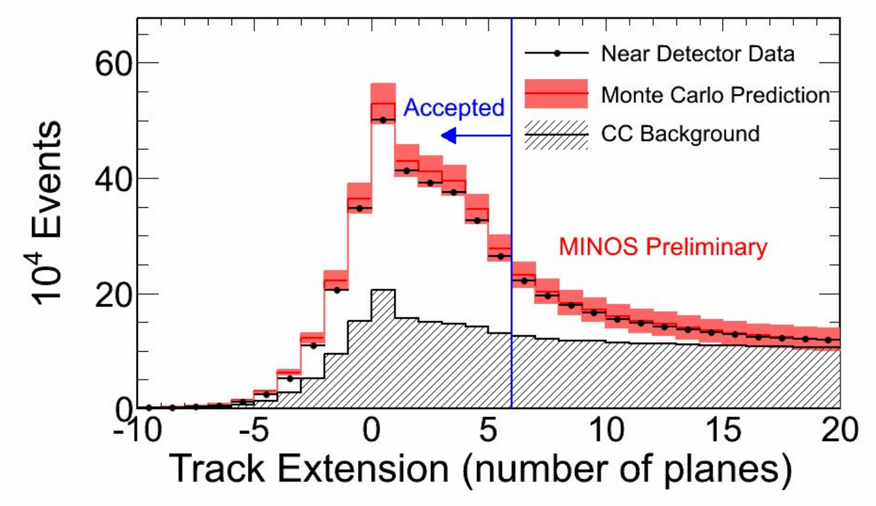

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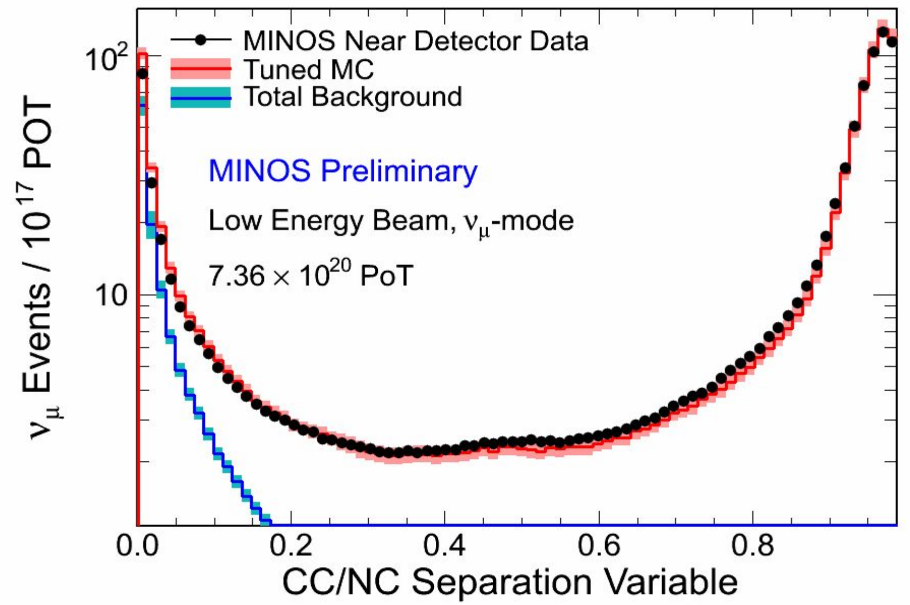
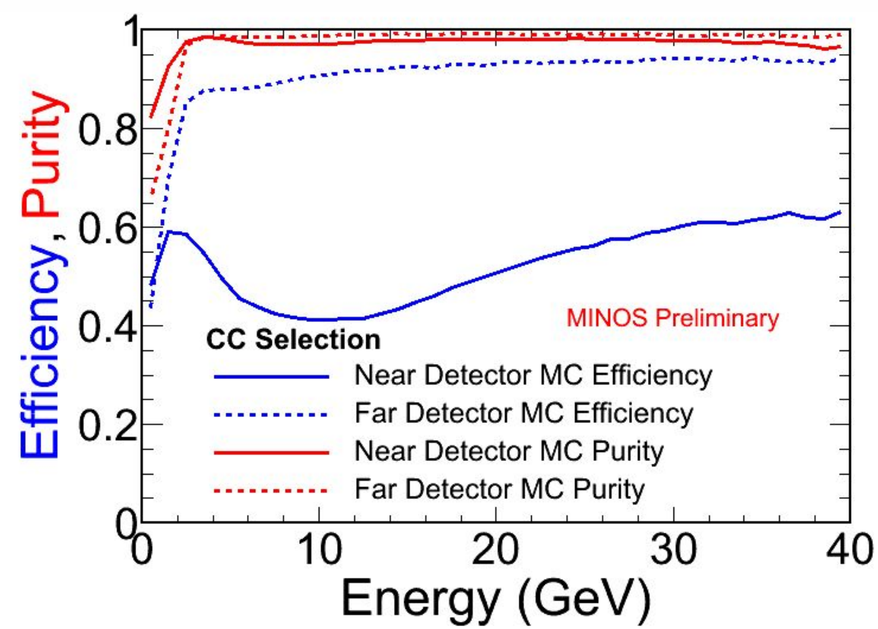
CC Event Selection

- CC and NC events are separated using a 4 variable kNN.
- CC selection is applied to events failing the NC selection criteria.
- 86% efficiency and 99% purity at the FD.





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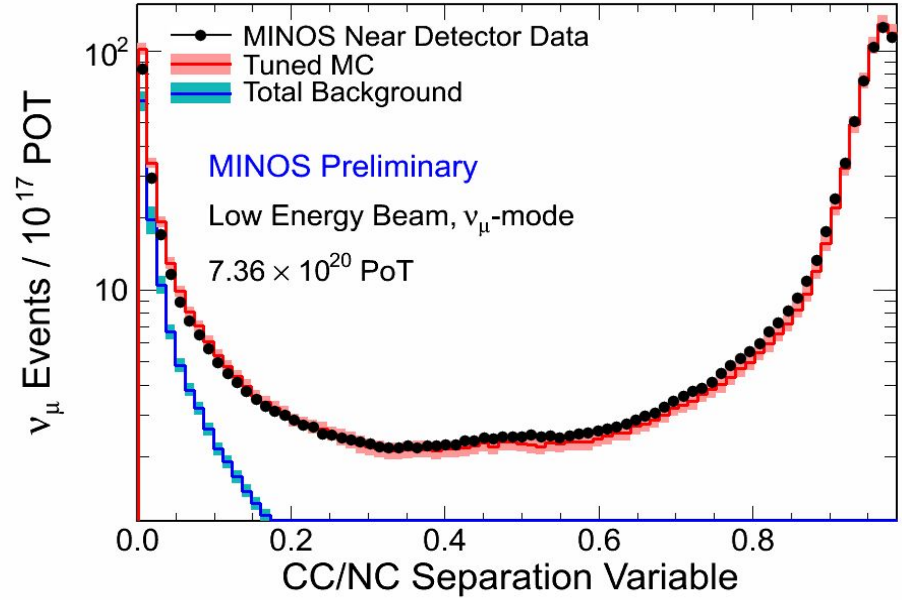
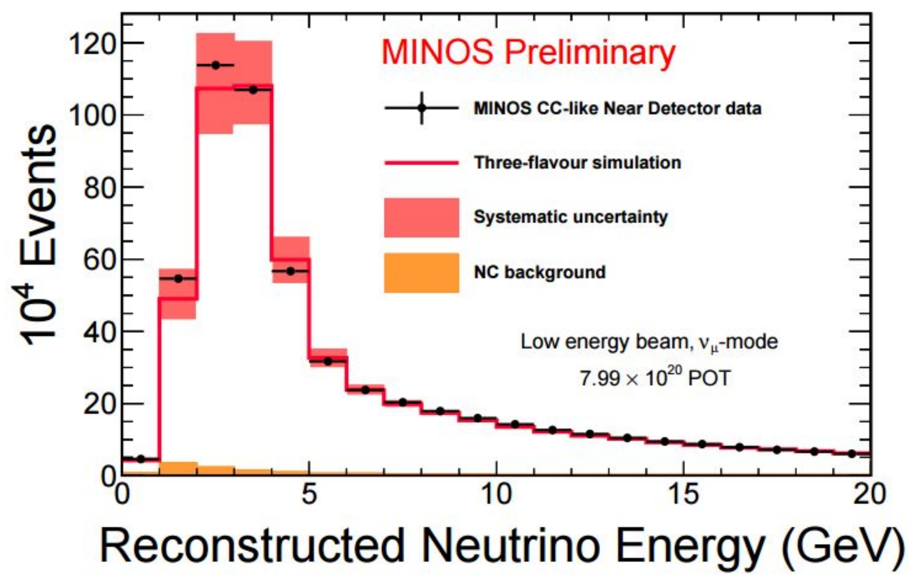
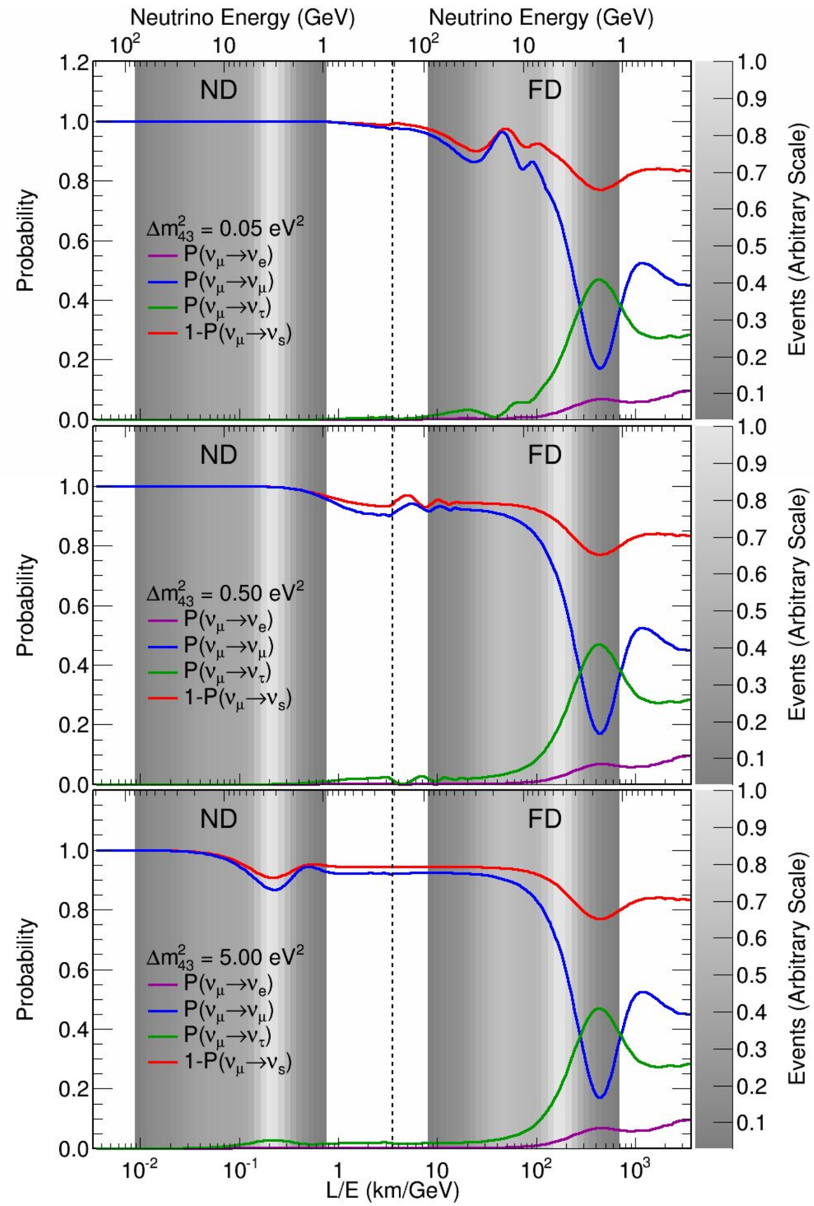




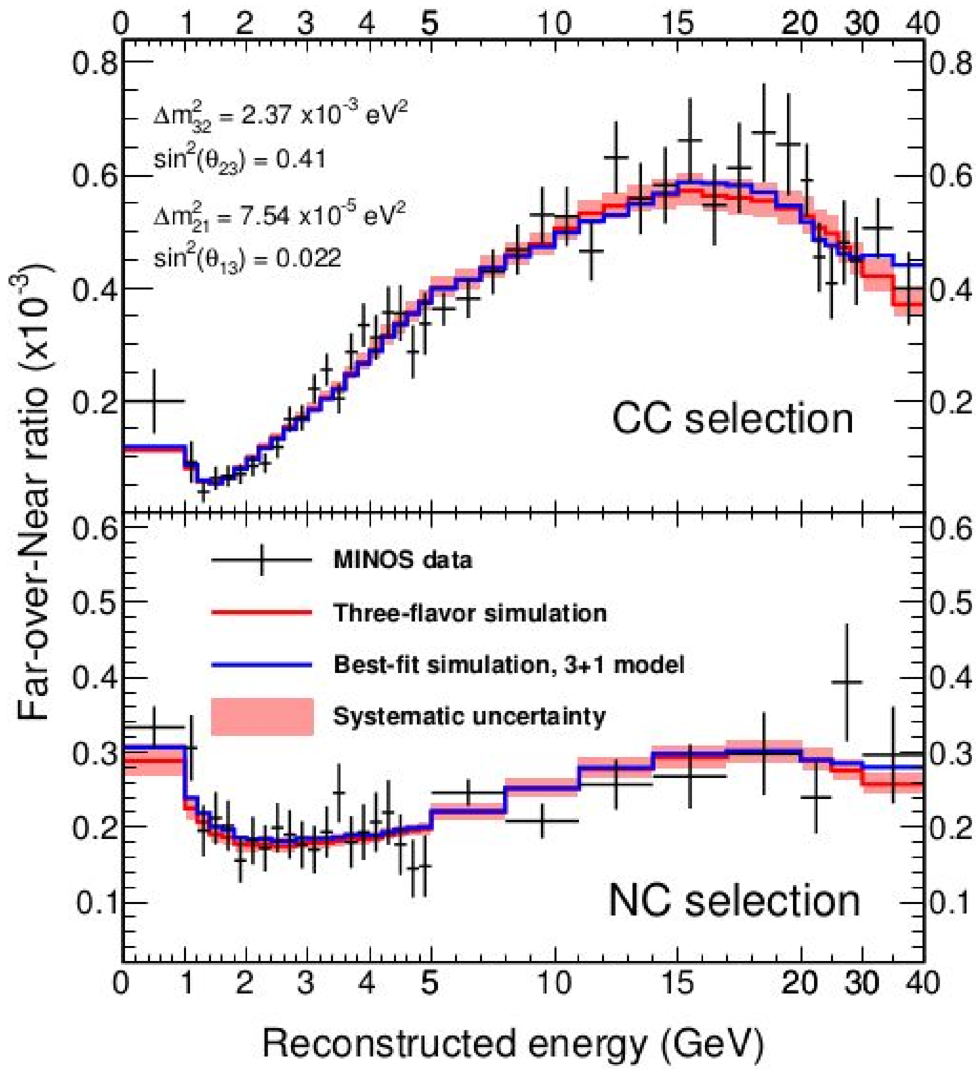
4-Flavor Oscillations

- Small Δm^2_{41}:
  - Oscillations at high energies in the FD.
  - No oscillations at the ND.
- Medium Δm^2_{41}:
  - Due to finite energy resolution, rapid oscillations at the FD average out.
  - Minimal oscillations at the ND.
- Large Δm^2_{41}:
  - Rapid oscillation at the FD.
  - Large oscillations at the ND.



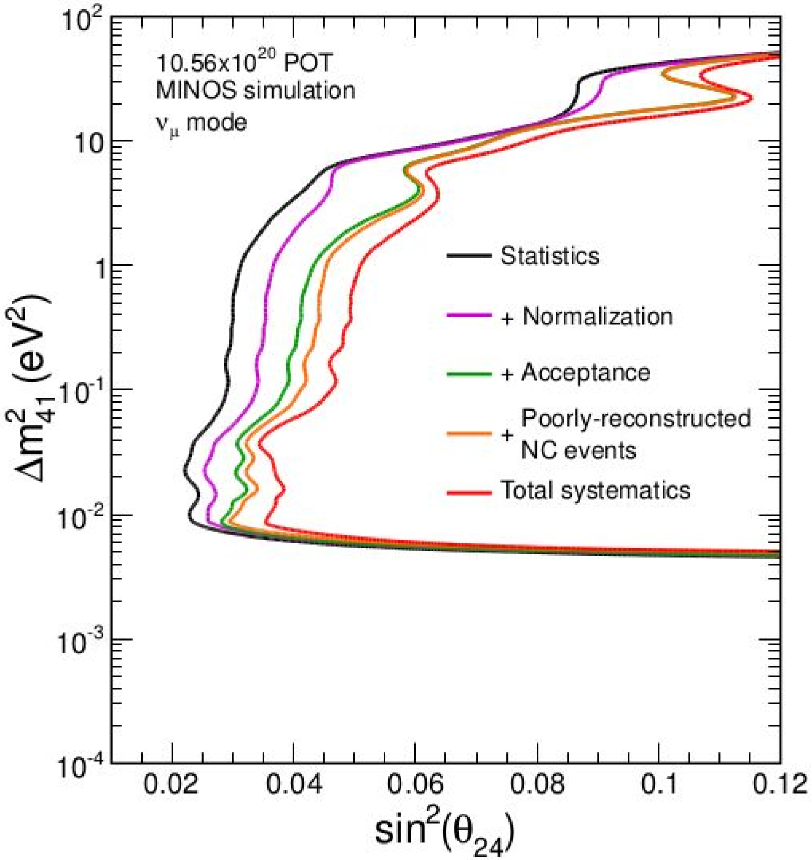
MINOS 4-Flavor Analysis Strategy

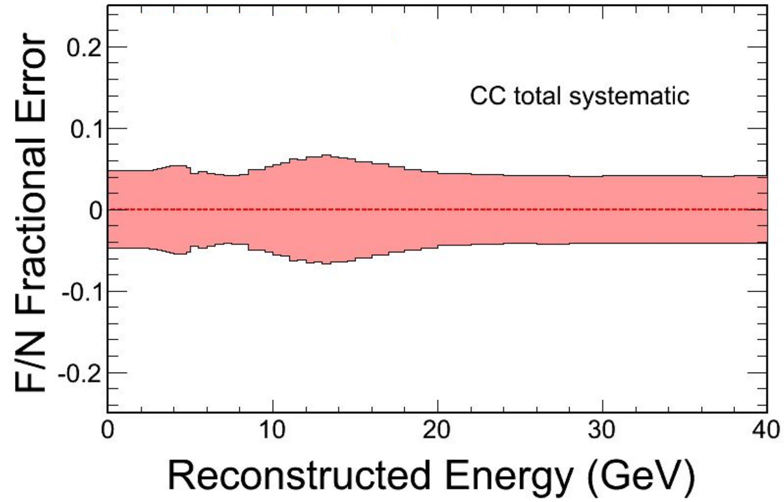
- Fit oscillated F/N MC ratio directly to F/N data ratio.
  - Include a constraint on the integrated ND rate.
- Fix parameters this analysis is not sensitive to (δ_{13}, δ_{14}, δ_{24}, and θ_{14}) to zero.
- Fit the NC and CC spectra simultaneously to determine θ_{23}, θ_{24}, θ_{34}, Δm^2_{32}, and Δm^2_{41}.

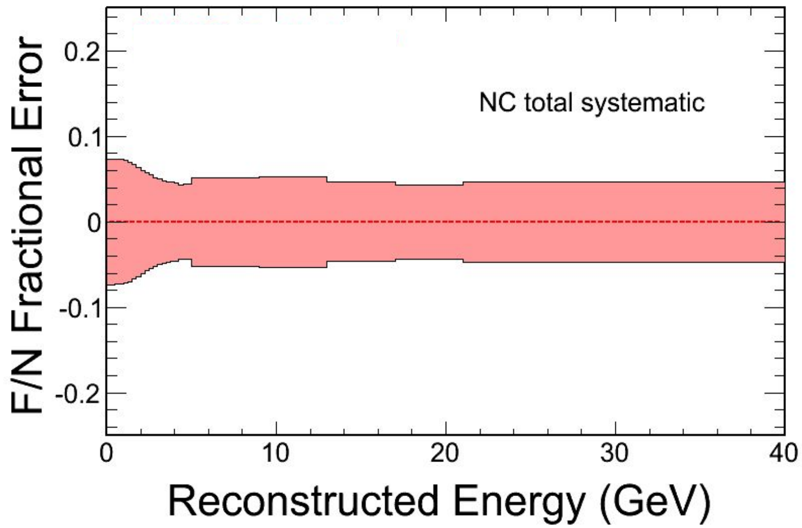


Total Systematics

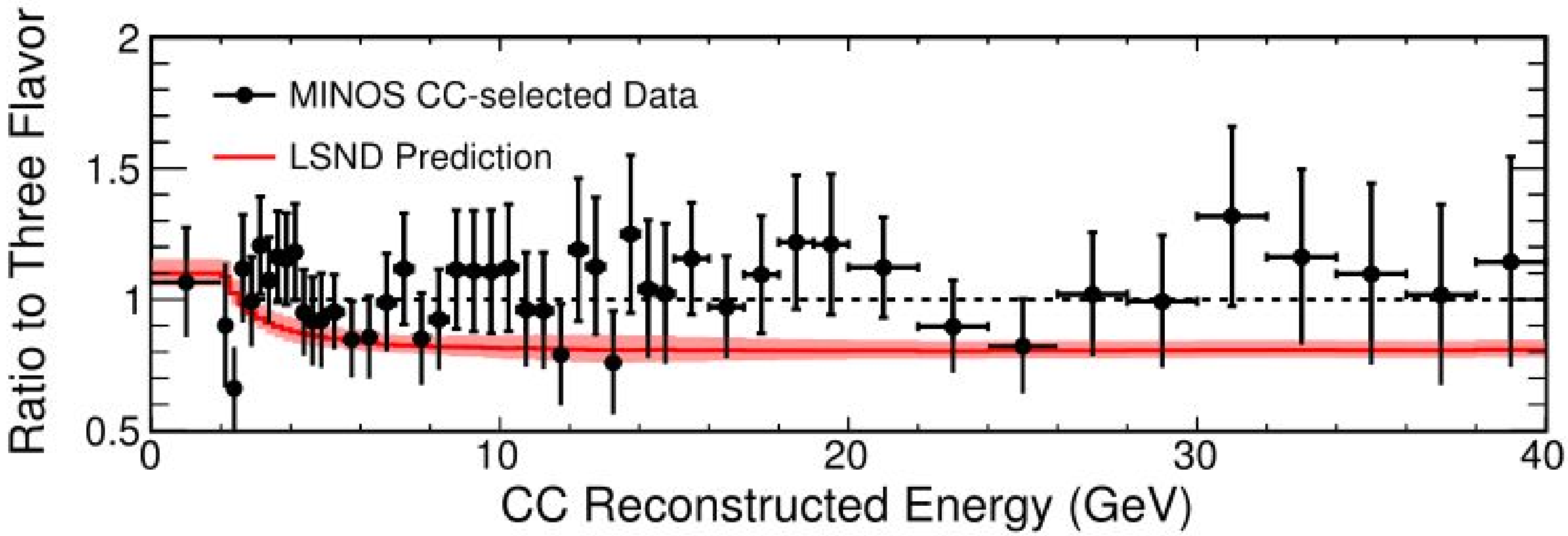
$$\chi^2 = \sum_{i=1}^{N}\sum_{j=1}^{N}(o_i - e_i)^T [V^{-1}]_{ij}(o_j - e_j)$$





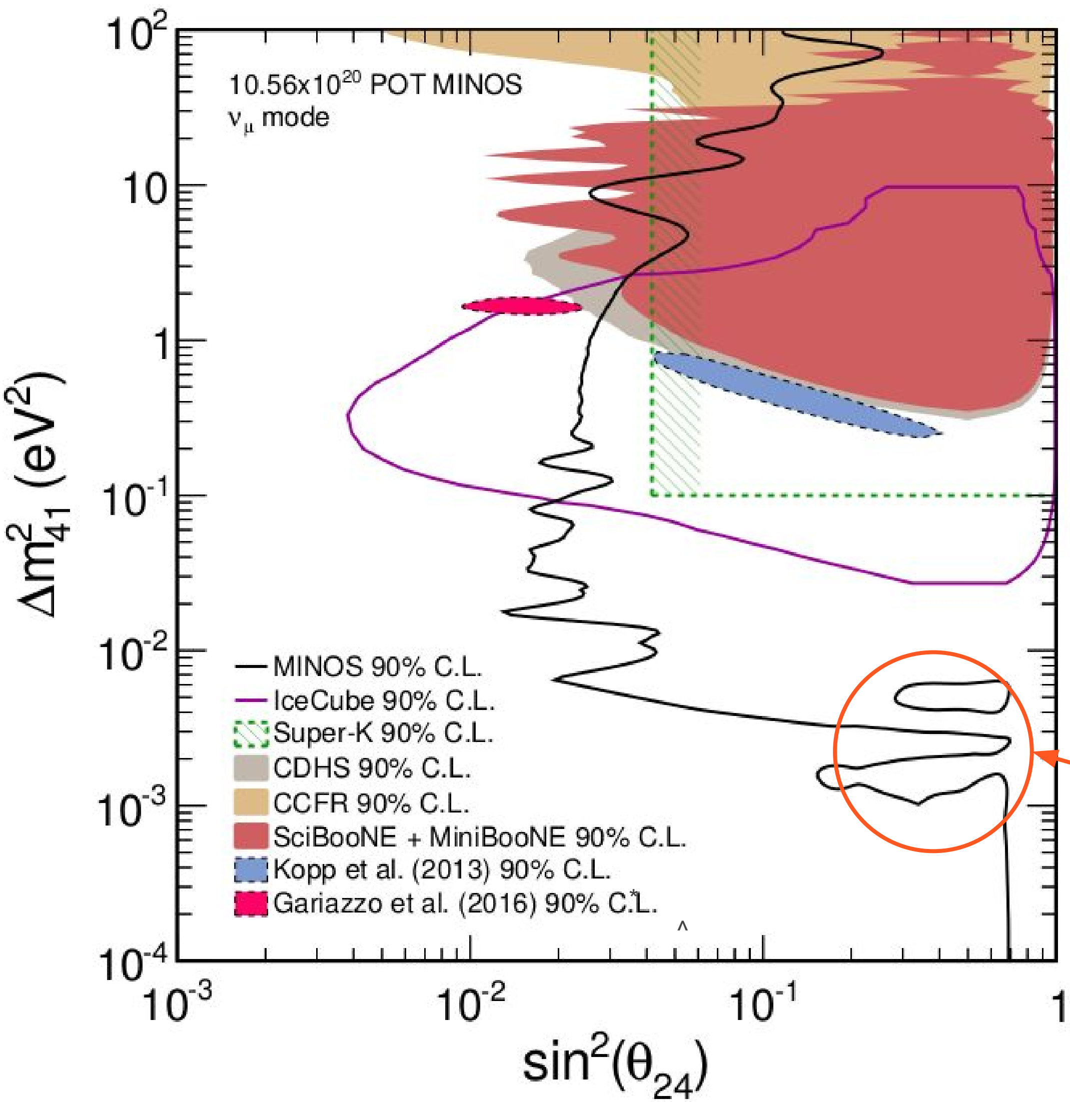


If a Light Sterile Neutrino Exists...



At LSND best fit point $\Delta m^2_{41} = 1.2\ \mathrm{eV}^2$, $\sin^2 2\theta_{\mu e} = 0.003$
$\sin^2 2\theta_{14} = 0.025$ (Daya Bay/Bugey-3 90% C.L. at $\Delta m^2_{41} = 1.2\ \mathrm{eV}^2$)
$\sin^2\theta_{24} = 0.12$
$\Delta\chi^2 = 38.0$

Disappearance Limit



MINOS 90% C.L. exclusion limit ranges over 6 orders of magnitude and is the strongest constraint on ν_μ disappearance into ν_s for low Δm^2_{41}.

Internal allowed region due to degenerate solutions.

[*] J. Kopp, P. Machado, M. Maltoni, T.Schwetz, JHEP 1305:050 (2013_

[^] S. Gariazzo, C. Giunti, M. Laveder, Y.F. Li, E.M. Zavanin, J.Phys.G**43**, 033001 (2016)

Degeneracies

$$P(\nu_\mu \to \nu_\mu) = 1 - 4\,|U_{\mu 3}|^2 \left(1 - |U_{\mu 3}|^2 - |U_{\mu 4}|^2\right) \sin^2 \Delta_{31}$$
$$- 4\,|U_{\mu 4}|^2\,|U_{\mu 3}|^2 \sin^2 \Delta_{43} - 4\,|U_{\mu 4}|^2 \left(1 - |U_{\mu 3}|^2 - |U_{\mu 4}|^2\right) \sin^2 \Delta_{41}$$

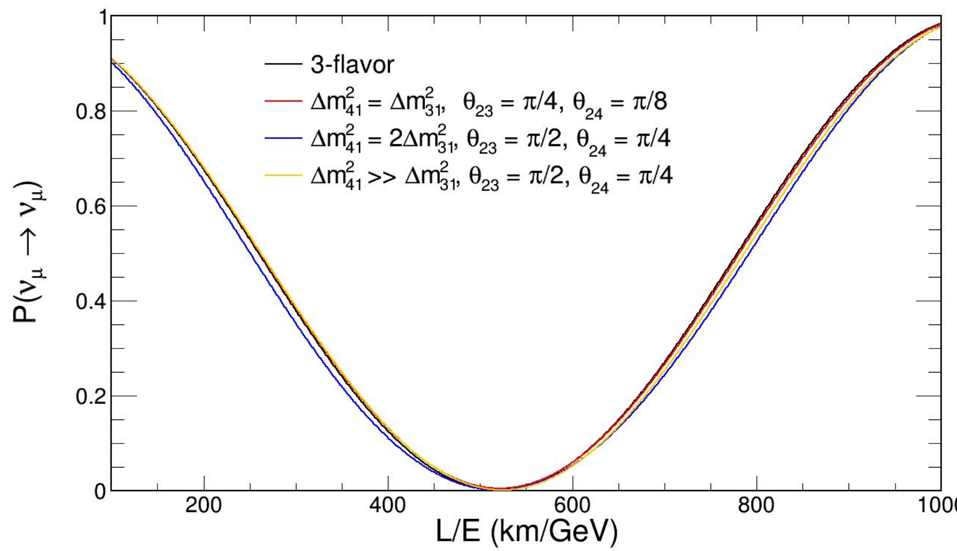
where $\Delta_{ij} = \dfrac{\Delta m^2_{ij} L}{4E}$

If:

- $\Delta_{41} \approxeq \Delta_{31}$
- $\Delta_{41} \approxeq 2\Delta_{31}$
- $\Delta_{41} \ll \Delta_{31}$

Certain combinations of θ_{23}, θ_{24}, and θ_{34} can produce 4-flavor solutions nearly indistinguishable from 3-flavor.

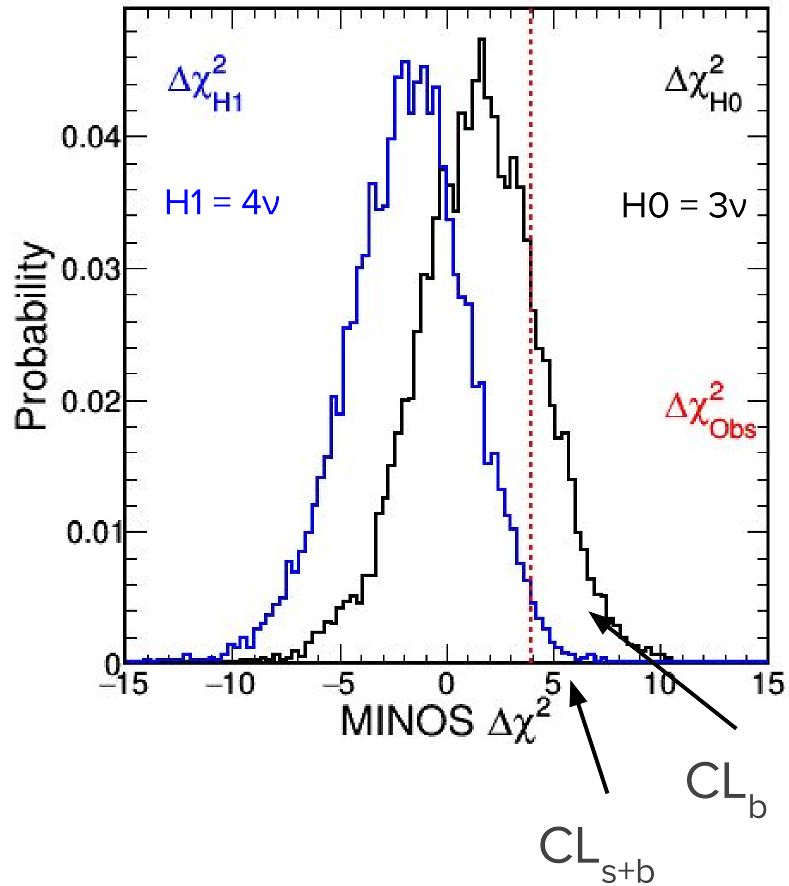
Run each fit five times ➔ each θ_{23} octant and mass hierarchy choice and the degenerate region.



Example degenerate scenarios

CL_s at MINOS

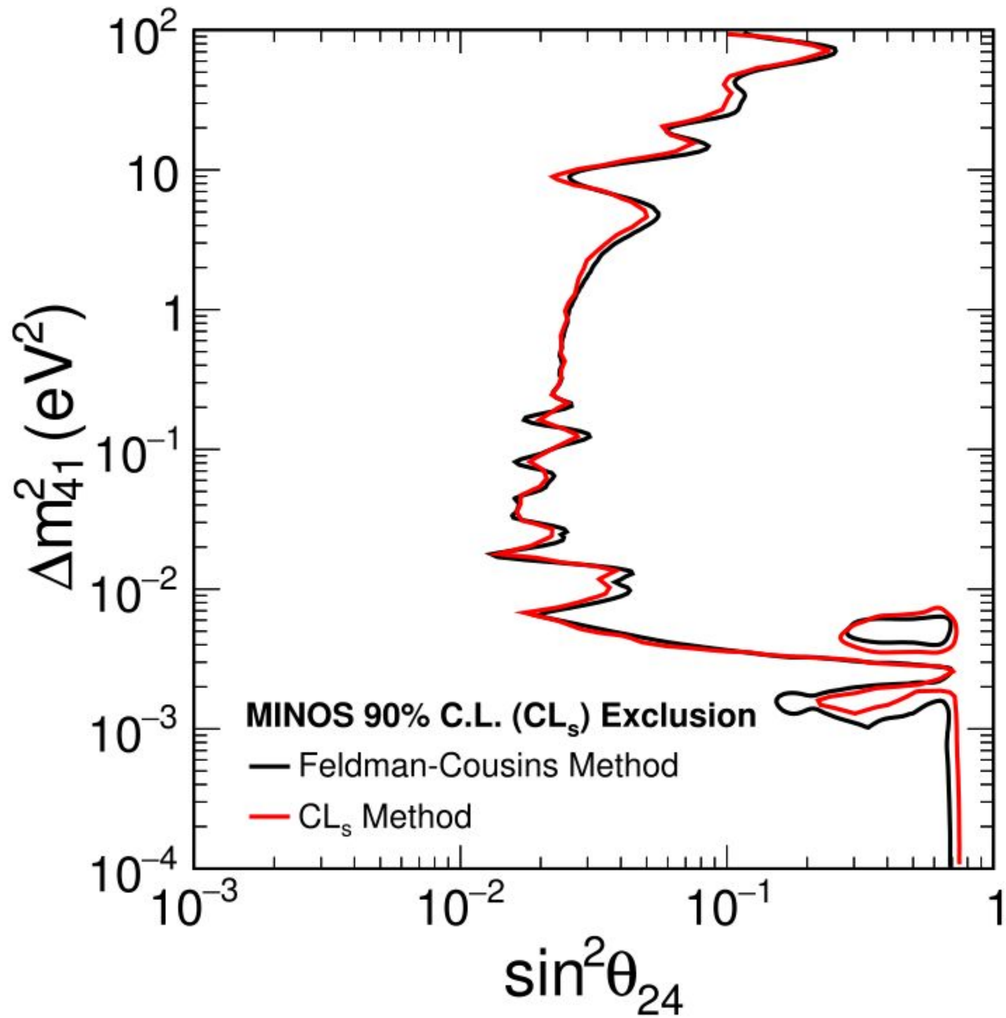
- MINOS has θ_{34} as a nuisance parameter.
  - Cannot use the Daya Bay's Gaussian CL_s method.
  - Use a fake experiment method.
- For each (Δm^2_{41}, θ_{24}) point:
  - Generate 3-flavor fake experiments using PDG parameters.
  - Generate 4-flavor fake experiments using the current (Δm^2_{41}, θ_{24}) point.
    - θ_{23}, θ_{34}, and Δm^2_{32} set to the best fit to data at each grid point.
- Fit each fake experiment to both the 3-flavor and 4-flavor hypotheses to build the $\Delta\chi^2$ distributions.



$$CL_s = CL_{s+b}/CL_b$$

CL_s Cross-Check

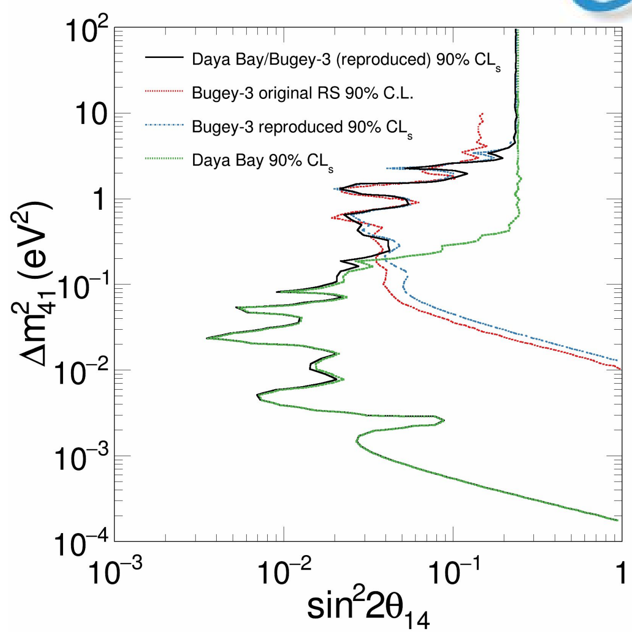
90% C.L. contours generated using the CL_s method are consistent with the limit constructed using the Feldman-Cousins method.

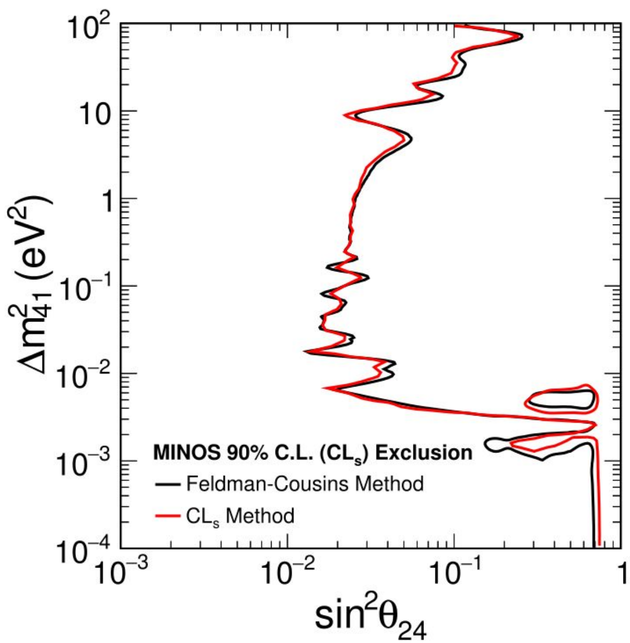


Daya Bay + Bugey-3 + MINOS

Combination Method

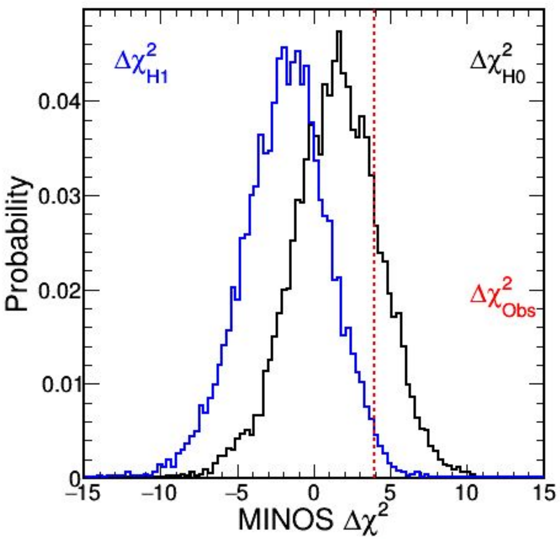
- Combining two disappearance experiments to set limits on $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2\theta_{24}$.
    - Surfaces from each experiment share the same y-axis but have different x-axes.
- Feldman-Cousin involves a best fit will all parameters free.
    - Constraining each experiment to a common Δm^2_{41} would be difficult without a joint fit framework.
- CL_s is an ideal solution
    - A local method
        - Δm^2_{41}, $\sin^2 2\theta_{14}$, and $\sin^2\theta_{24}$ are always fixed.



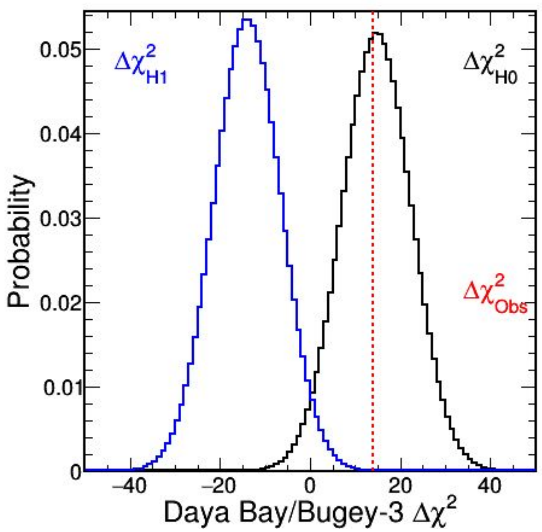


Combining a Single Point

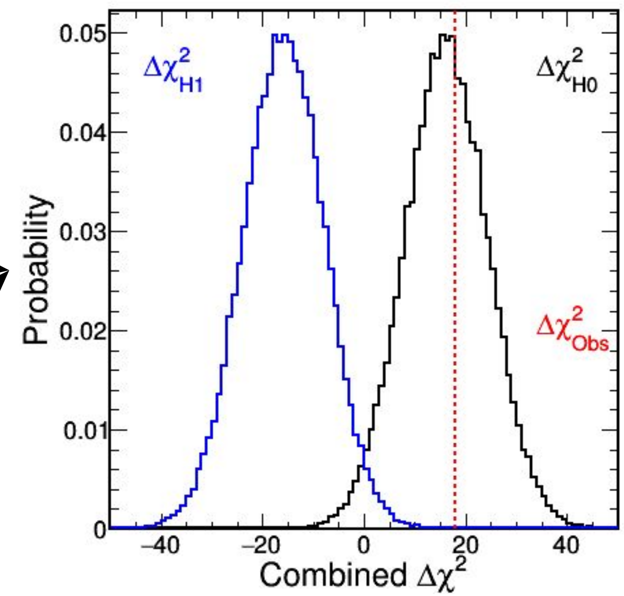
Need to be able to calculate CL_s at a single $(\sin^2 2\theta_{14}, \sin^2\theta_{24}, \Delta m^2_{41})$ point.



Draw MINOS $\Delta\chi^2$ values from fake experiments.



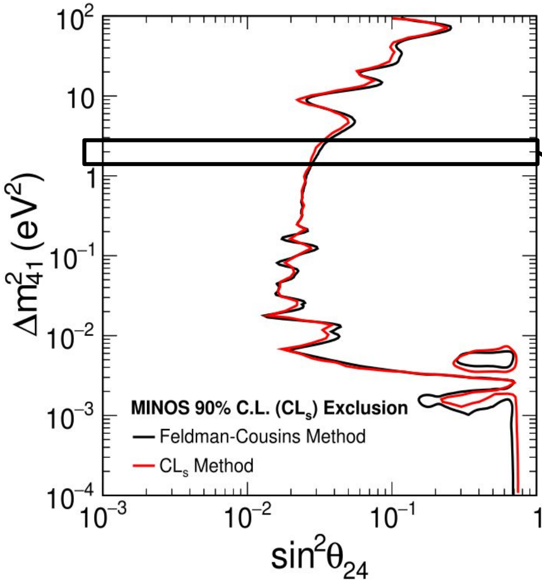
Draw Daya Bay/Bugey-3 $\Delta\chi^2$ values from Gaussian distributions.

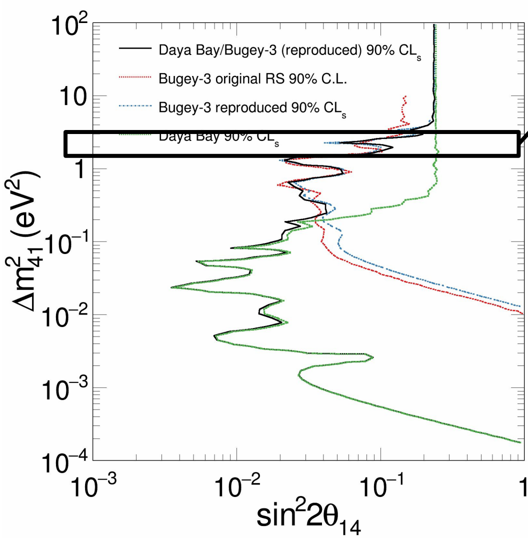


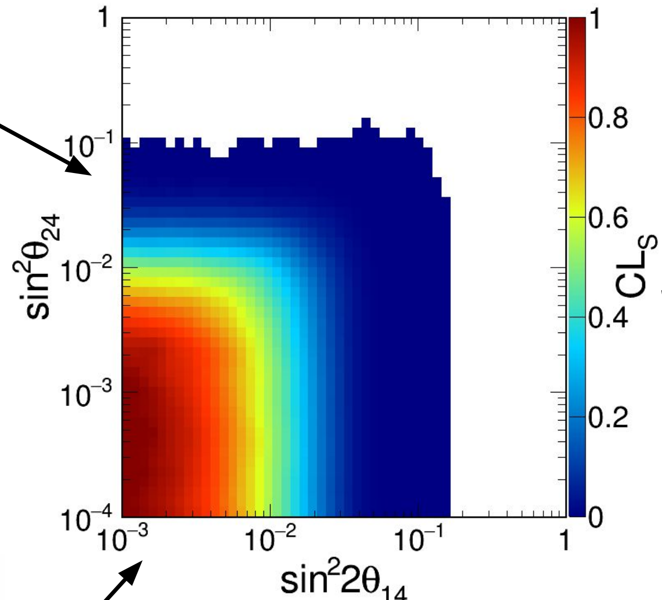
MINOS and Daya Bay/Bugey-3 have uncorrelated systematics so:

$$\Delta\chi^2_{combo} = \Delta\chi^2_{DB} + \Delta\chi^2_{MINOS}$$

Combining a Δm^2_{41} Row

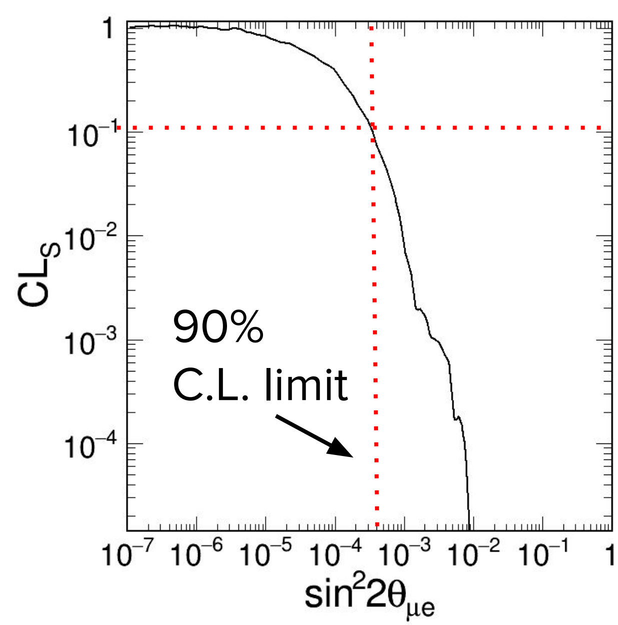






For a fixed Δm^2_{41}, calculate CL$_s$ at each ($\sin^2 2\theta_{14}$, $\sin^2\theta_{24}$) point.

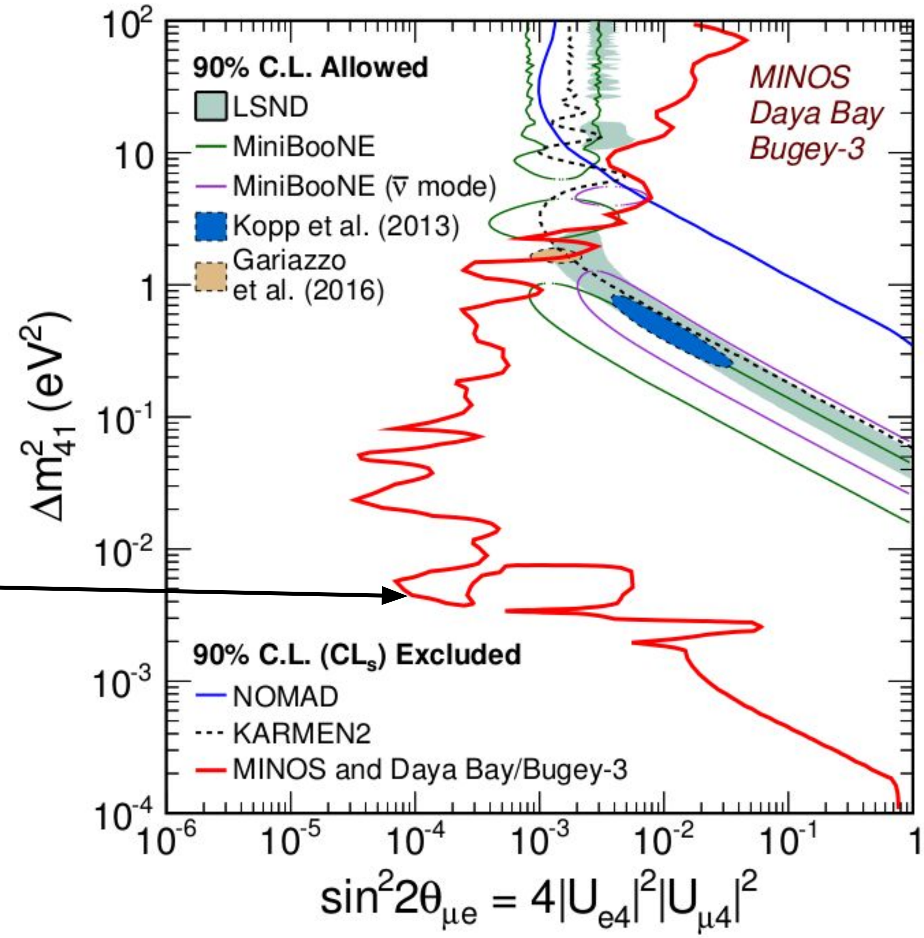
- Convert CL$_s$ from a 2D function of ($\sin^2 2\theta_{14}$, $\sin^2\theta_{24}$) to 1D function of $\sin^2 2\theta_{\mu e}$
  - Using $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2\theta_{24}$
- Multi-valued, so pick the largest CL$_s$ per bin as a conservative choice.



Combined - 90% C.L.

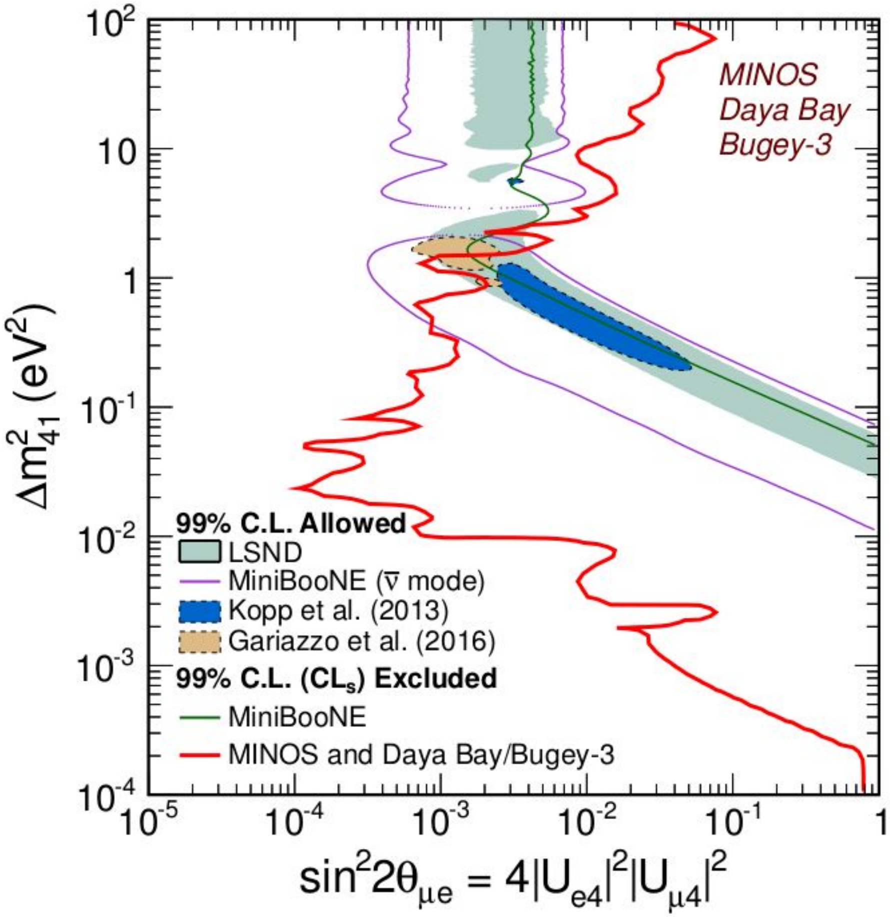
The combined 90% C.L. limit excludes appearance allowed regions for $\Delta m^2_{41} < 0.8$ eV^2.

Structure at low Δm^2_{41} is due to the degenerate regions.

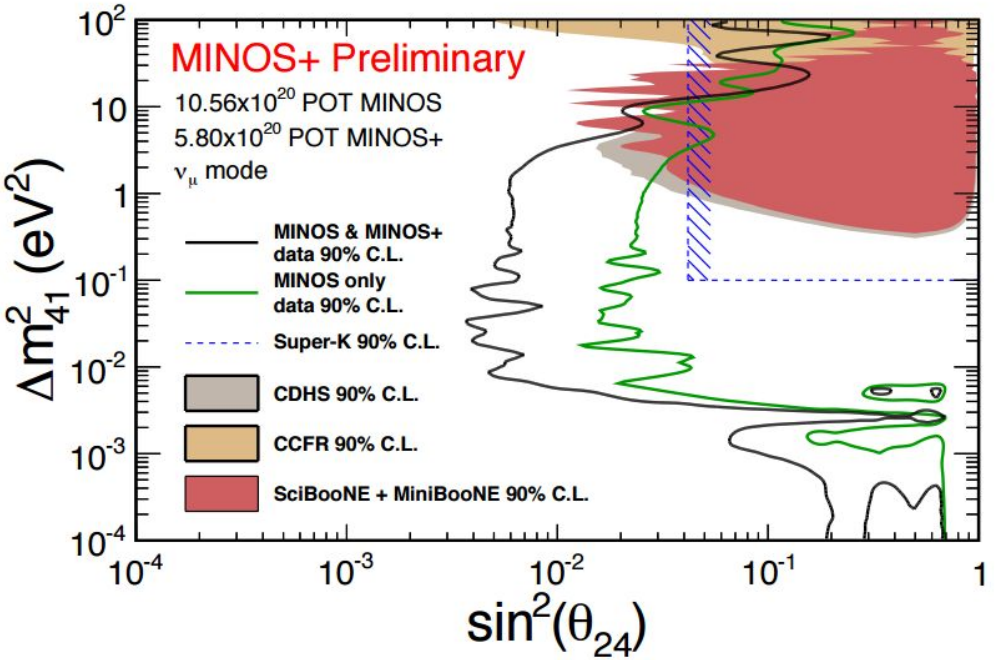


Combined - 99% C.L.

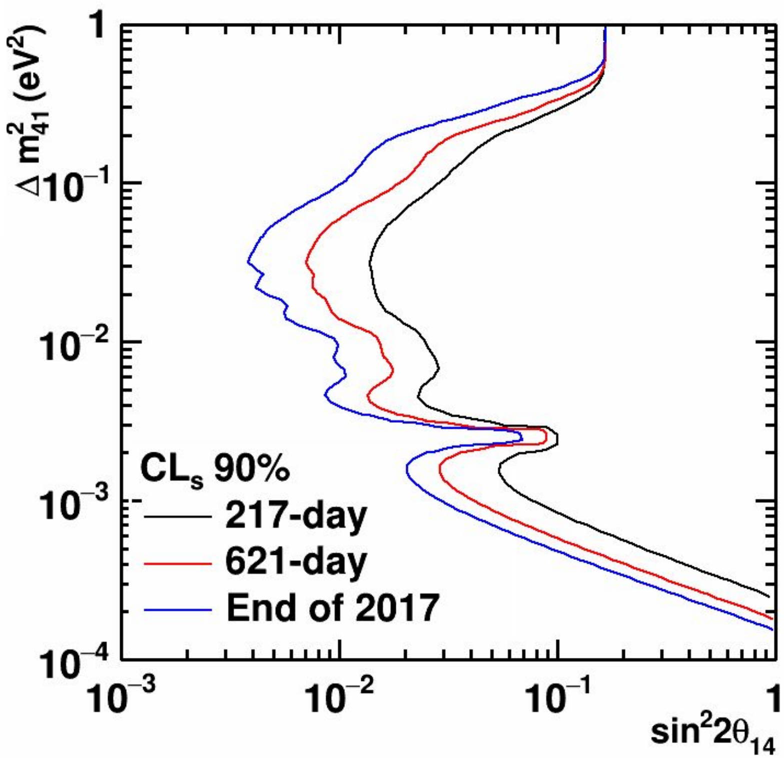
The combined 99% C.L. limit excludes appearance allowed regions for $\Delta m^2_{41} < 0.4\ \mathrm{eV}^2$, and it excludes almost all of the 99% C.L. global allowed region.



The Future



Sensitivities including expected data collected by Daya Bay through the end of 2017 show a significant improvement in constraining $\sin^2 2\theta_{14}$.



A preliminary analysis adding the first ½ of MINOS+ data shows a large improvement, especially at mid-$\Delta\chi^2$ values due to ~10x increase in statistics at high energy.

Conclusions

MINOS

- Improved accounting for ND oscillations, systematic uncertainties and handling of 4-flavor degeneracies.
- Extended its 90% C.L. exclusion limit over 6 orders of magnitude in Δm^2_{41}.

Daya Bay

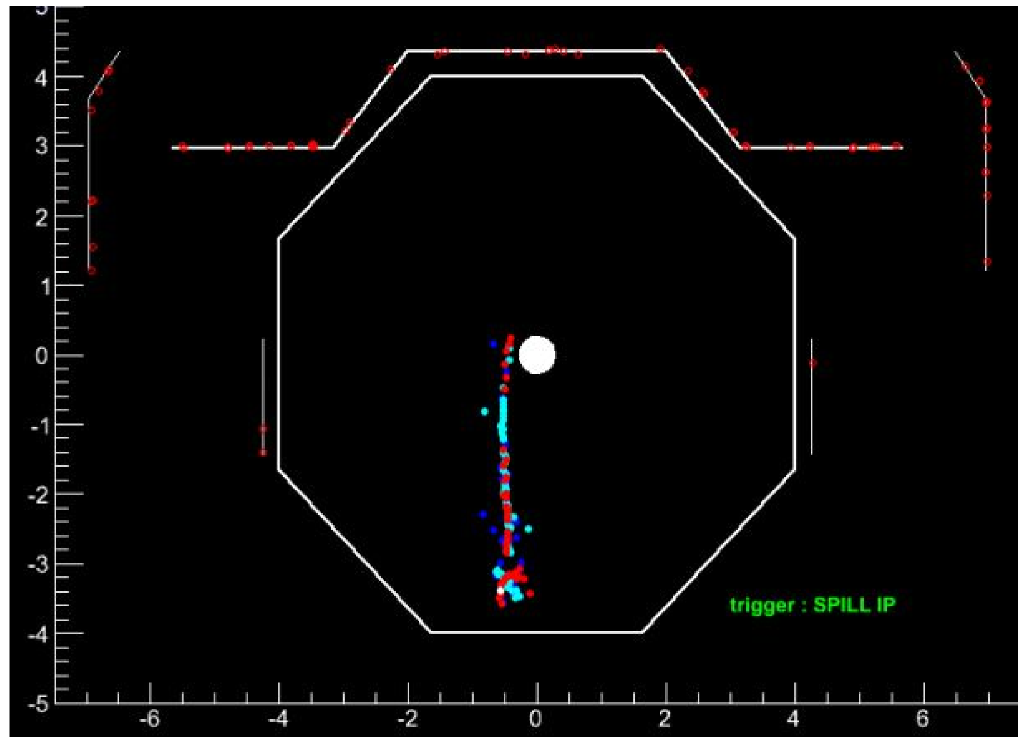
- Factor of 2 improvement over 6-AD analysis on the constraints of $\sin^2 2\theta_{14}$.
- Daya Bay + Bugey-3 extends the exclusion contour up to $\Delta m^2_{41} \approxeq 5$ eV^2.

MINOS and Daya Bay/Bugey-3 Combination

- Through close collaboration, Daya Bay and MINOS were able to use the CL_s technique to combine their disappearance limits to extract equivalent appearance limits, assuming the 4-flavor model.
- Increases the tension between appearance and disappearance sterile neutrino searches for $\Delta m^2_{41} < 1$ eV^2.

End of MINOS

- On 29 June 2016, MINOS and MINOS+ officially ended data taking.
- A special thanks to Fermilab and the Soudan mine crew for making it possible to collect 2.61×10^{21} proton-on-target of data!



Final MINOS golden neutrino event

Thank you!

The Daya Bay experiment is supported in part by the Ministry of Science and Technology of China; the U.S. Department of Energy; the Chinese Academy of Sciences; the CAS Center for Excellence in Particle Physics; the National Natural Science Foundation of China; the Guangdong provincial government; the Shenzhen municipal government; the China General Nuclear Power Group; the Research Grants Council of the Hong Kong Special Administrative Region of China; the Ministry of Education in Taiwan; the U.S. National Science Foundation; the Ministry of Education, Youth and Sports of the Czech Republic; the Joint Institute of Nuclear Research in Dubna, Russia; the NSFC-RFBR joint research program;and the National Commission for Scientific and Technological Research of Chile.

The MINOS experiment is supported by the U.S. Department of Energy; the United Kingdom Science and Technology Facilities Council; the U.S. National Science Foundation; the State and University of Minnesota; and Brazil's FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo), CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico), and CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior). We are grateful to the Minnesota Department of Natural Resources and the personnel of the Soudan Laboratory and Fermilab. We thank the Texas Advanced Computing Center at The University of Texas at Austin for the provision of computing resources.

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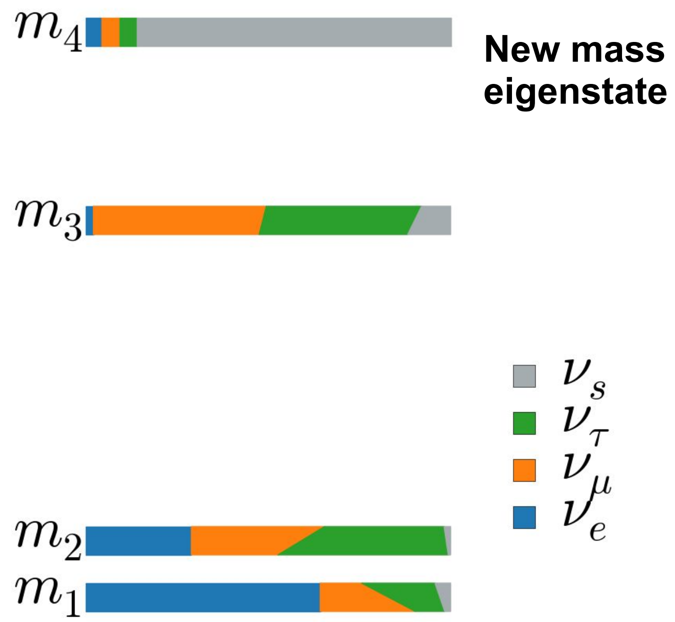
Backup

3+1 Formalism



$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

For Daya Bay $\bar{\nu}_e \to \bar{\nu}_e$:

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L/E) = 1 - 4 \sum_{k>j} |U_{ek}|^2 |U_{ej}|^2 \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right)$$

→ Sensitive to $|U_{e4}|^2$

+

For MINOS $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$:

$$P_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu}(L/E) = 1 - 4 \sum_{k>j} |U_{\mu k}|^2 |U_{\mu j}|^2 \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right)$$

→ Sensitive to $|U_{\mu 4}|^2$

For LSND & MiniBooNE $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$:

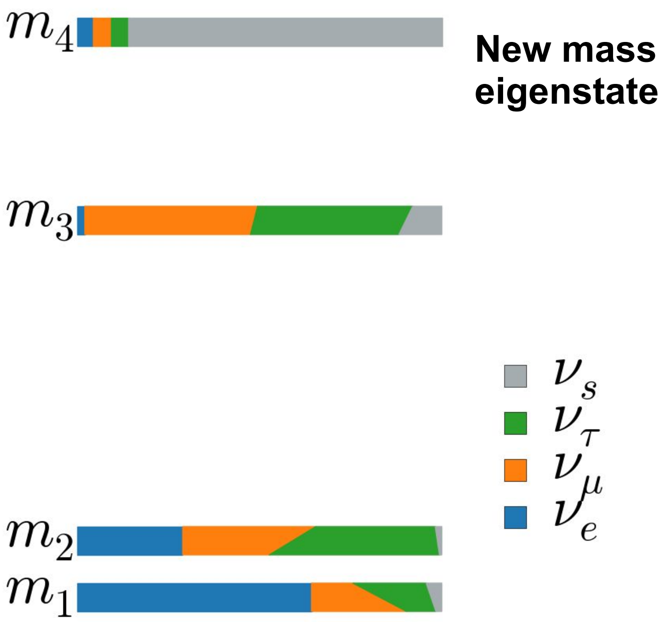
→ Sensitive to $|U_{e4}|^2 |U_{\mu 4}|^2$

$$P_{\nu_\mu \to \nu_e}(L/E) \approx 4 |U_{e4}|^2 |U_{\mu 4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \approx P_{\bar{\nu}_\mu \to \bar{\nu}_e}$$

when $\Delta m^2_{41} \gg |\Delta m^2_{32}|$

3+1 Formalism

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$



For $U = R_{34}R_{24}R_{14}R_{23}R_{13}R_{12}$

$$|U_{e4}|^2 = \sin^2\theta_{14},$$

$$|U_{\mu4}|^2 = \sin^2\theta_{24}\cos^2\theta_{14},$$

$$4|U_{e4}|^2|U_{\mu4}|^2 = \sin^2 2\theta_{14}\sin^2\theta_{24} \equiv \sin^2 2\theta_{\mu e}$$

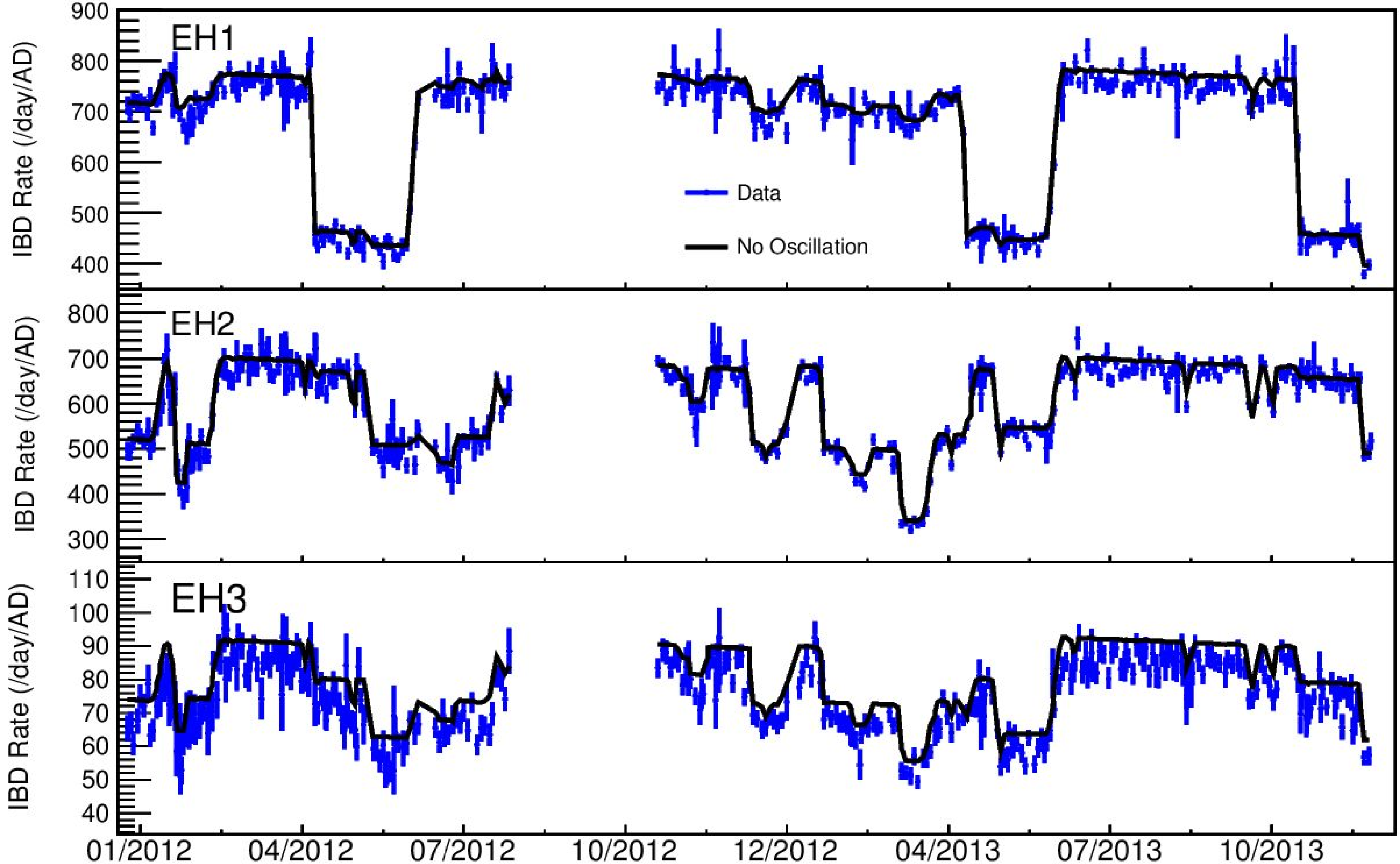
Daya Bay

MINOS

LSND&
MiniBooNE

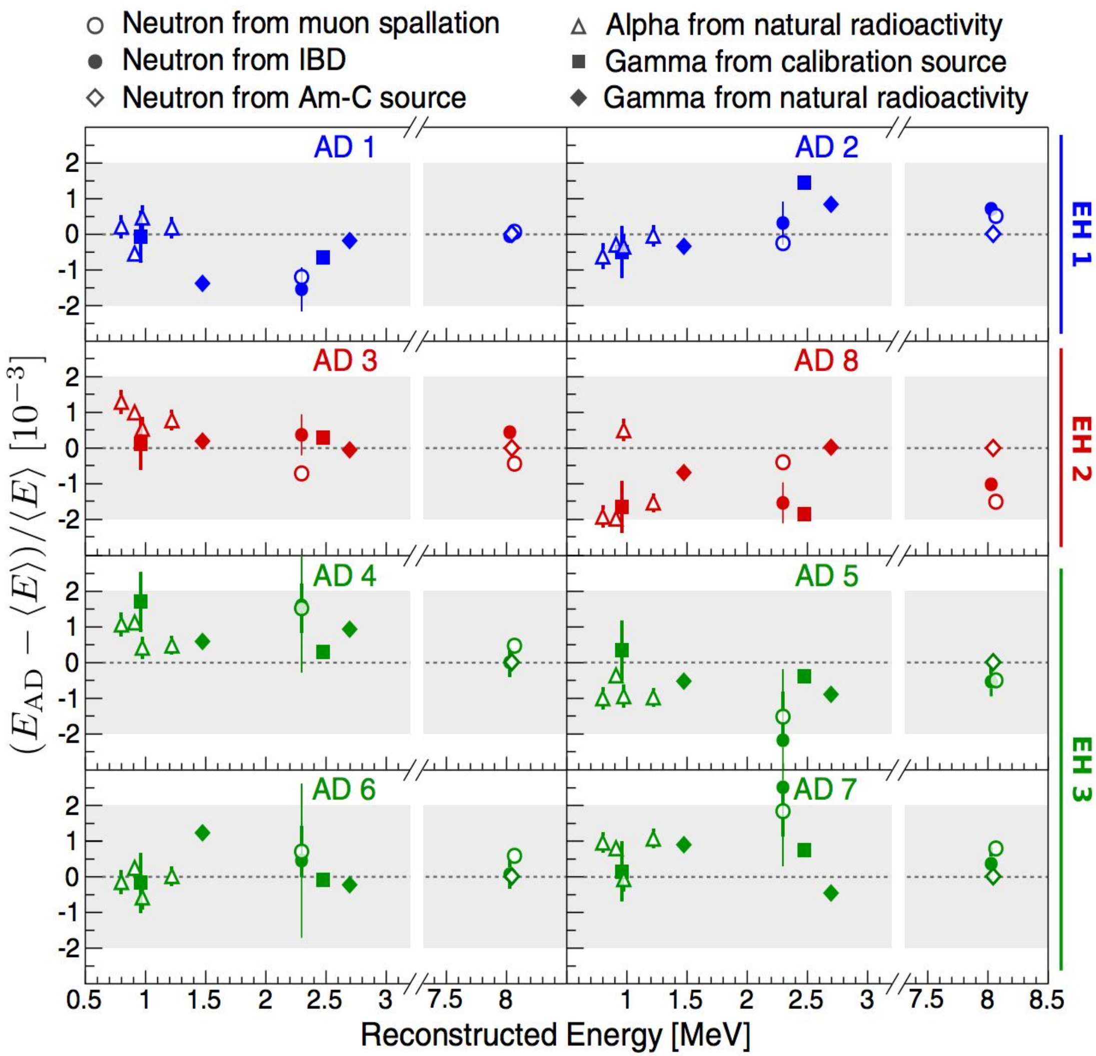
621 days

Event Rates



621 days

Calibration



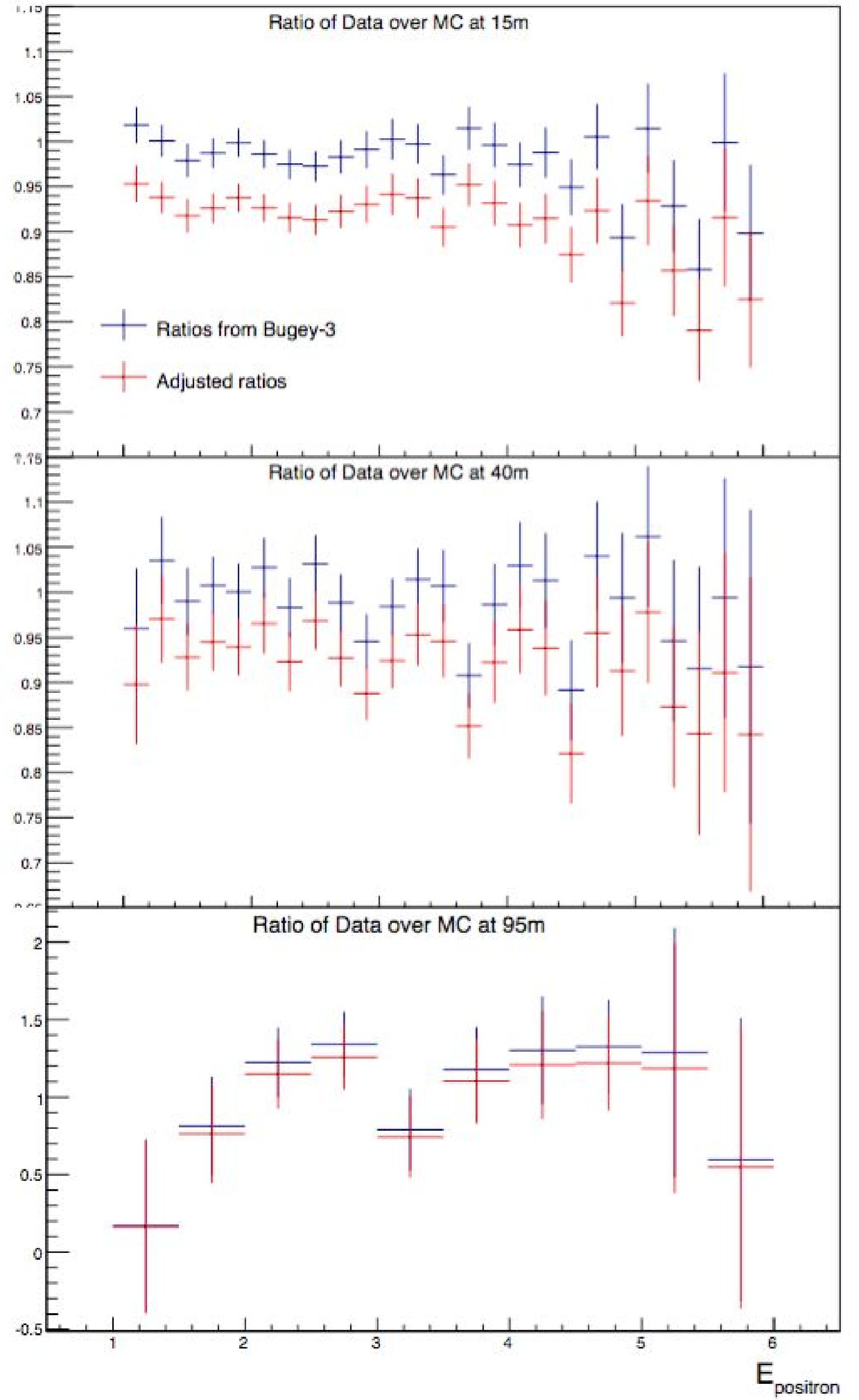
The uncertainty of relative energy improves from 0.35% for 6-AD to 0.2% for 621-day period

Design of Daya Bay

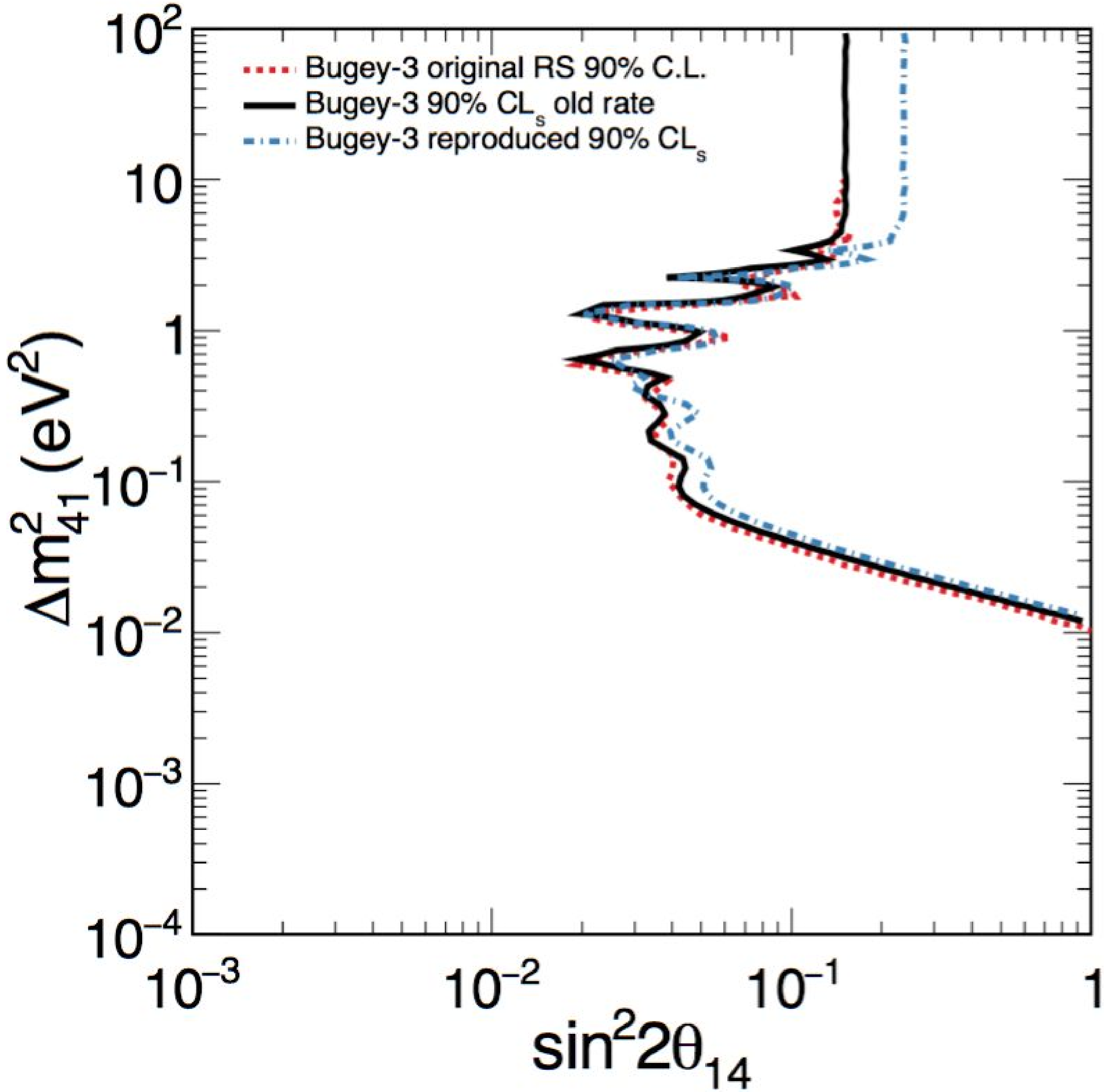
- Relative Measurement
  - Near and far detectors:
    minimize reactor related uncertainties
  - Identical modules:
    minimize detector related uncertainties
- Low Backgrounds
  - Large overburden at far site(860 m.w.e.)
- Large statistics
  - Large target mass: 8x20-ton detectors
  - Large neutrino flux: 6x2.9 GWth reactors

Bugey Ratio

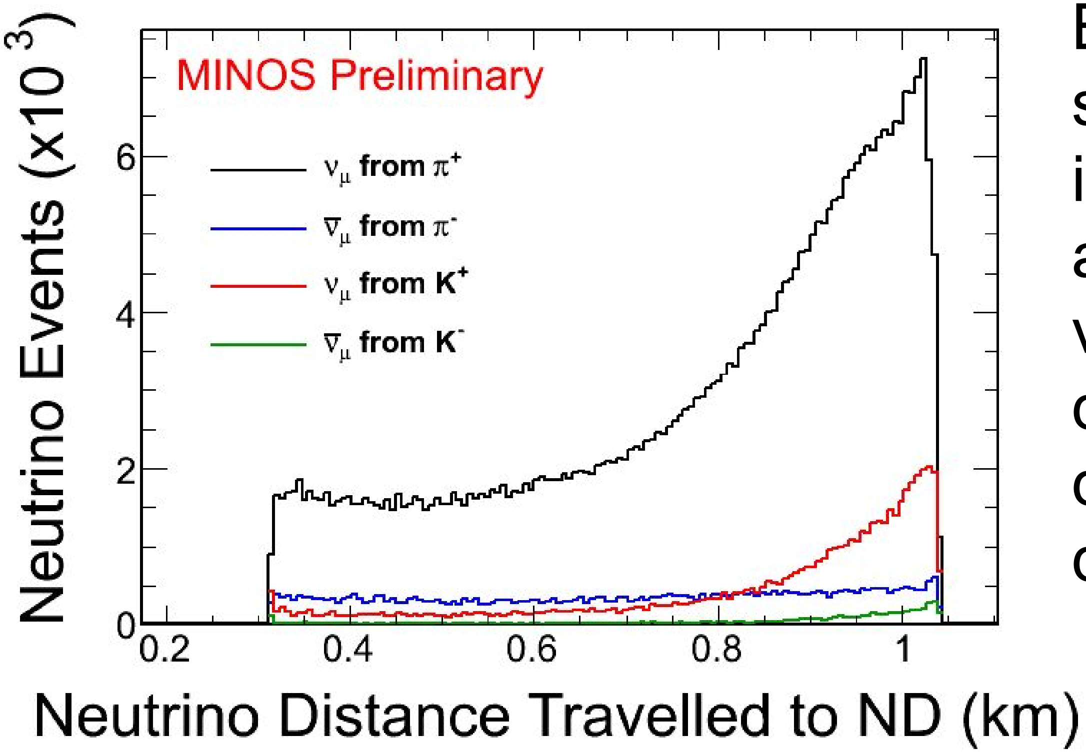
- Major difference is due to
  - Difference between ILL+Vogel and Huber+Mueller model
  - Difference in neutron lifetime



Bugey-3 Reproduced



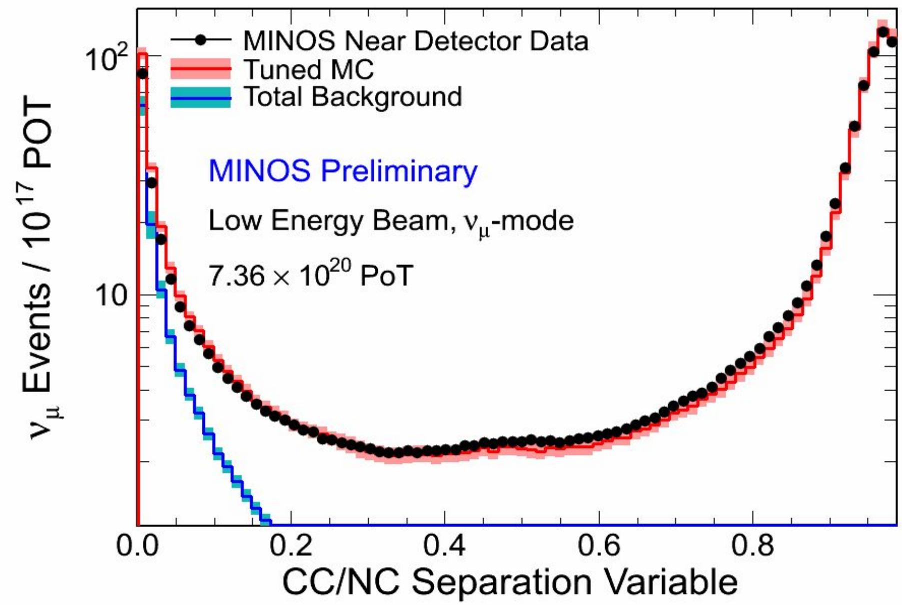
Varying Baseline

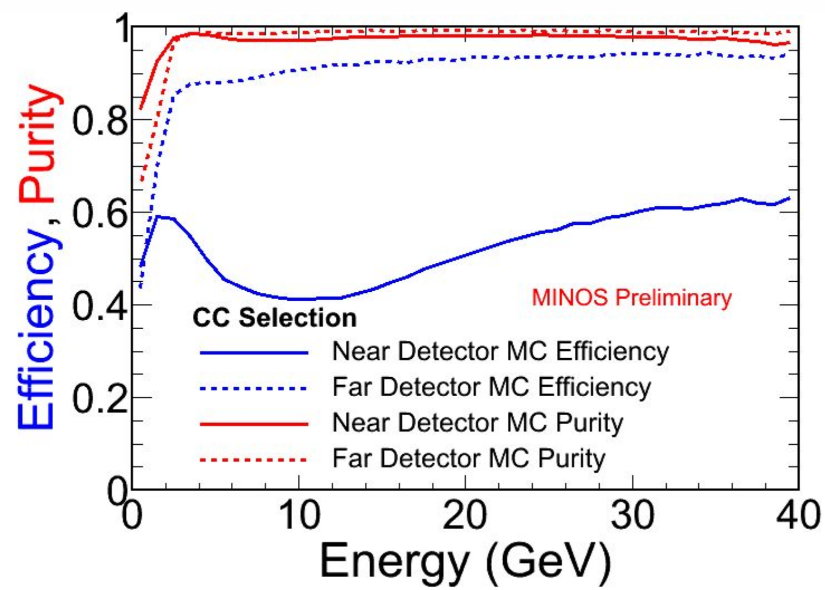


Because we now allow for short-baseline oscillations, it is crucial that we account for the baseline varying due to the distribution of hadron decay points within the decay pipe.

CC Event Selection

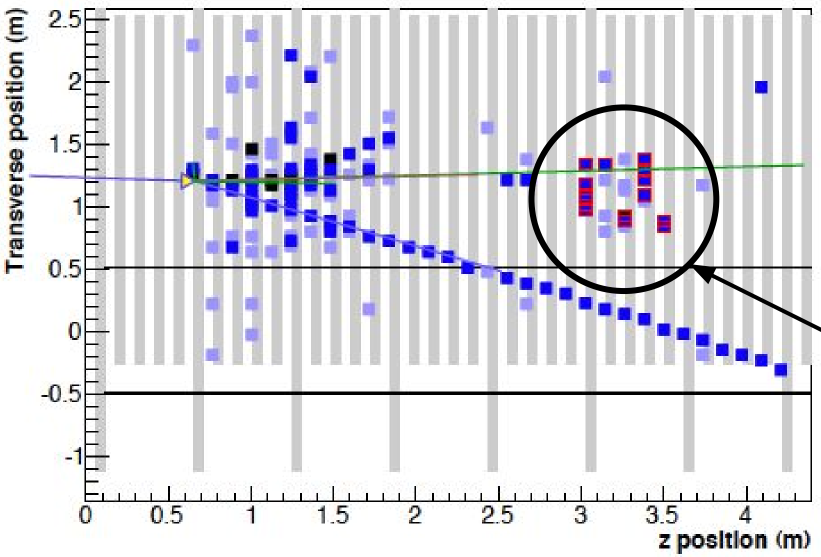
- CC and NC events are separated using a 4 variable kNN.
  - Number of scintillator planes in a track.
  - Mean pulse height of all track hits.
  - Ratio of low pulse height to high pulse height hits.
  - Ratio of pulse height on the track to all hits.
- CC selection is applied to events failing the NC selection criteria.
- 86% efficiency and 99% purity at the FD.



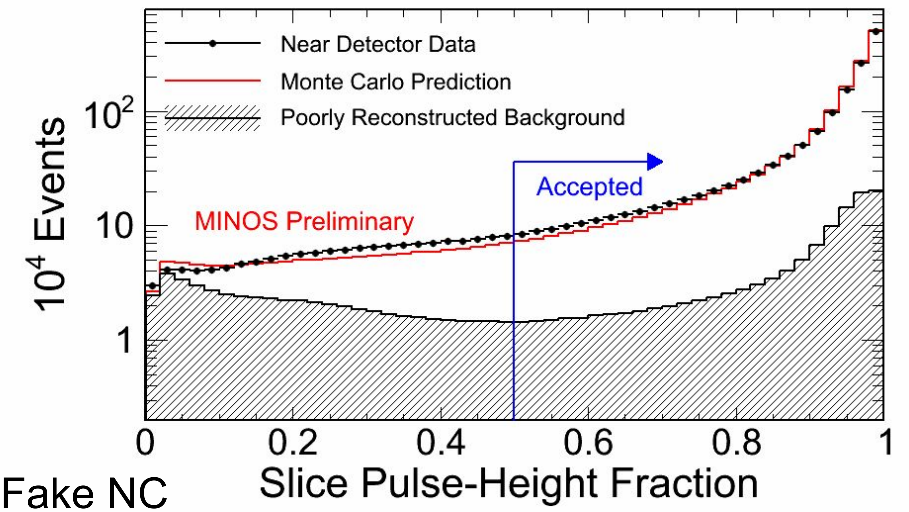


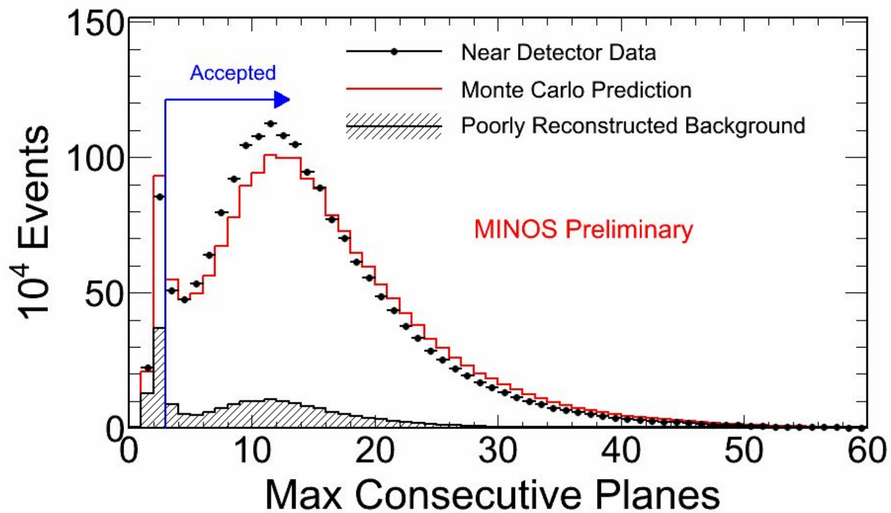
Poorly Reconstructed Events

High rate in Near Detector requires temporal and spatial clustering ➜ may cause split or merged events



Fake NC event





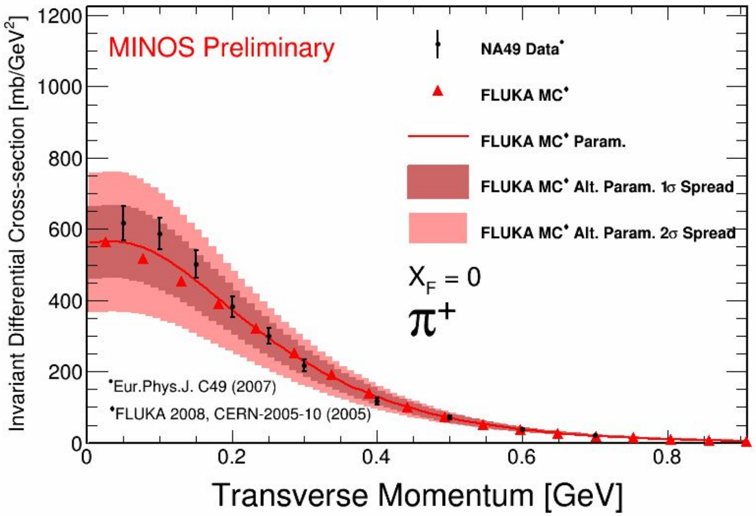
Minimize with pre-selection cuts on:

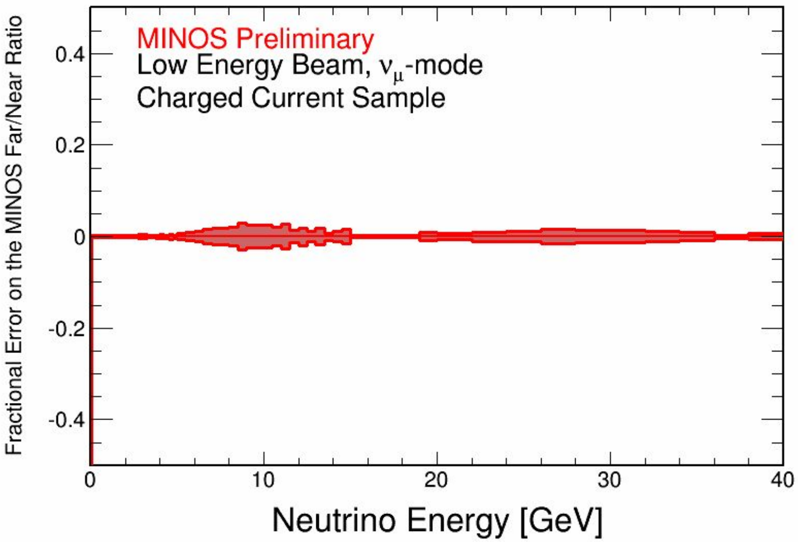
- Fraction of pulse height in cluster
- The maximum number of consecutive planes

Remaining data/MC disagreement is taken as a systematic uncertainty.

Beam Systematics

- Due to the possibility of ND oscillations, it is not possible to constrain the beam flux using a fit to ND data.
  - Need to reassess beam systematics.
- Fit a FLUKA simulation of the NA49 target to the BMPT parameterization.
- Vary fit parameters within their errors to create a collection of physically feasible alternate differential cross-section parameterizations.
- Scale up the errors given by the fit until the collection of alternate parameterizations cover the difference between the FLUKA MC and NA49 data.
- Use this collection of alternate parameterizations to reweight the ND and FD neutrino spectra and create a covariance matrix.
- The resulting F/N error is small.



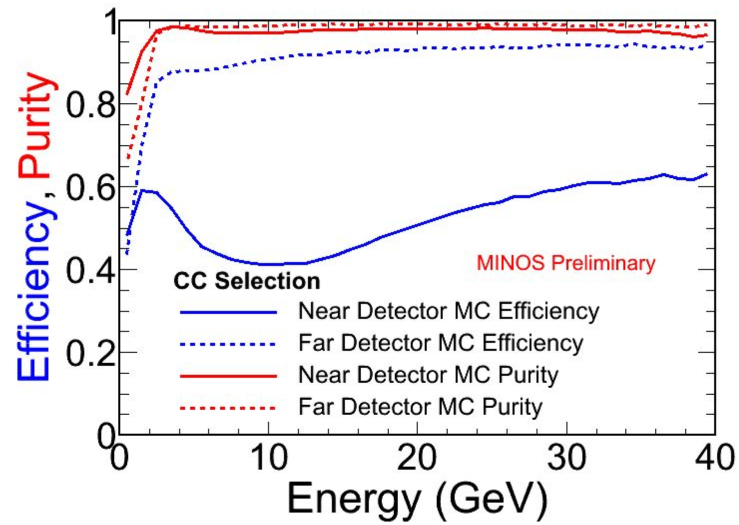


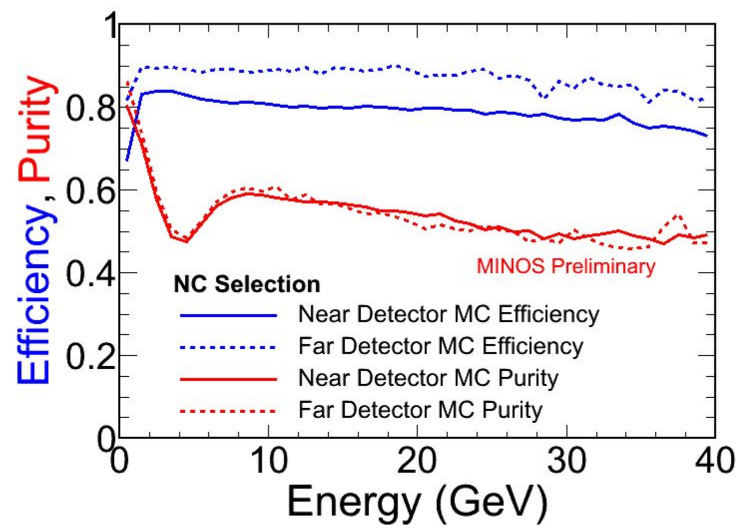
ND Acceptance Systematics

- Acceptance uncertainties are determined by comparing the effect of varying cuts on data/MC at the ND compared to the nominal cuts.
- Examined the effect of:
  - Varying the fiducial volume
  - Varying the containment criteria
  - Excluding tracks ending near the join between the calorimeter and spectrometer
  - Varying how close tracks can come to the coil hole
- Together, these have the largest effect on our sensitivity.

CC and NC Selection

- MINOS was optimized for identifying n_m CC interactions.
- Identifying NC events is more difficult.
  - 89% efficiency and 61% purity at the FD
  - Main background is inelastic n_m CC events.
  - 97% of n_e CC event are selected as NC.





Combination Method

- MINOS has $\Delta\chi^2$ distributions for 3-flavor and 4-flavor fake experiments at each (Δm^2_{41}, $\sin^2\theta_{24}$) grid point.
- Daya Bay and Bugey-3 have Gaussian $\Delta\chi^2$ 3-flavor and 4-flavor distributions at each (Δm^2_{41}, $\sin^2 2\theta_{14}$) grid point.
- For a fixed Δm^2_{41}, calculate CL_s at each ($\sin^2 2\theta_{14}$, $\sin^2\theta_{24}$) point.
  - Using the distribution of $\Delta\chi^2_{combo}$ for both 3-flavor truth and 4-flavor truth, construct the combined CL_b and CL_{s+b}.
  - Systematic uncertainties are uncorrelated between MINOS and Daya Bay + Bugey-3, so $\Delta\chi^2_{combo}$ is the sum of $\Delta\chi^2$ drawn from the MINOS distribution and the Daya Bay+Bugey-3 distribution for either 3-flavor or 4-flavor truth.
- Pick the largest CL_s for a given $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14}\sin^2\theta_{24}$ as a conservative choice.

Degeneracies

$$P(\nu_\mu \to \nu_\mu) = 1 - 4\,|U_{\mu 3}|^2 \left(1 - |U_{\mu 3}|^2 - |U_{\mu 4}|^2\right) \sin^2 \Delta_{31} \\ - 4\,|U_{\mu 4}|^2\,|U_{\mu 3}|^2 \sin^2 \Delta_{43} - 4\,|U_{\mu 4}|^2 \left(1 - |U_{\mu 3}|^2 - |U_{\mu 4}|^2\right) \sin^2 \Delta_{41}$$

where $\Delta_{ij} = \dfrac{\Delta m_{ij}^2 L}{4E}$

If $\theta_{23} \approx \pi/2$ and any of:

- $\Delta_{41} \approx \Delta_{31}$
- $\Delta_{41} \approx 2\Delta_{31}$
- $\Delta_{41} \ll \Delta_{31}$

θ_{24} can take on the role of θ_{23} leading to 4-flavor oscillations degenerate with the 3-flavor scenario

Run each fit five times ➔ each θ_{23} octant and mass hierarchy choice and the degenerate region.